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QUANTITATIVE STRUCTURAL DESIGN CRITERIA BY STATISTICAL METHODS

VOLUME II. THE PHILOSOPHY AND IMPLEMENTATION OF THE NEW PROCEDURE

INNES BOUTON, MEL FISK,

and

D. J. TRENT

TECHNICAL REPORT AFFDL-TR-67-107, VOLUME II

JUNE 1968

AIR FORCE FLIGHT DYNAMICS LABORATORY
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

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FOREWORD

This report was prepared by North American Rockwell Corporation for the Structures Division, Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio, under Air Force Contract No. AF33(615)-3755, Project No. 1367, "Structural Design Criteria," Task No. 136714, "Structural Loads Criteria Simulation Techniques."

The study and analysis, on which this report is based, were accomplished by the Methods and Criteria Unit of the Structures and Design Department in the Space Division and by the Structural Loads group of the Dynamics Technology Department of the Los Angeles Division during the period from February 1967 to November 1967. Mr. M. Fisk was Program Manager for North American Rockwell. Mr. George E. Muller of the AFFDL (FDTR) was the Project Engineer.

The contractor's designation of this report is SID 67-495-2. This report was submitted by the authors in February 1968.

Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

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ABSTRACT

Exploratory research, needed to develop quantitative structural design criteria for aerospace vehicles, has been conducted to relate the probabilistic nature of design, operational, and environmental experiences to the structural performance of aerospace vehicles. Volume I presents a critique of present and proposed approaches to structural design criteria. Volume II presents the philosophy and implementation of the new procedure. Volume III formulates two computer programs for the procedure and presents the user's instructions for the programs.

Volume II develops the philosophy of a statistically-based, deterministic system. This system forms the foundation of the recommended new procedure, which is a modification of the Present (Factor of Safety) Structural Design System, not a completely different approach. The concept that the structural system is expected to have the capability to survive both overload and under-strength situations is propounded. Requirements for providing these two capabilities are identified separately and explicitly. These requirements are based on statistical considerations, but the resulting design conditions are established as deterministic requirements. This is the key to making the new procedure practical and administrable. A one page summary of the procedure is presented on page 122. An application of the procedure to the F-100 airplane demonstrates how to use the technique. Problems that may be encountered in implementing the procedure are discussed.

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LIST OF SYMBOLS

ASIP	Aircraft structural integrity program
ASIS	Actual State Information System
CRT	Computer output visual display via Cathode Ray Tube
$\Delta p_{25}(x_i)$	Probability that a particular system whose mean is x_j will fail in the interval $x_i + \Delta x_i$
Δx_i	Main program basic integration interval
Δx_j	Basic integration interval for strength subroutines
DSIS	Desired State Information System
exp	Base of Naperian logarithms, e = 2.71828
FATREL	Fatigue strength, time dependent, structural reliability computer program
FDI	Fatigue damage index
FS	Factor of safety
γ_s	Coefficient of strength variation = $\frac{\sigma_s}{\mu_s}$
H	Altitude
M	Mach number
M/sec^2	Meters per second per second
M_x	Wing (tail) bending moment, about x-axis
M_z	Fuselage side bending moment, about z-axis
μ_s	Mean of normal strength distribution

μ_T	Mean strength (theoretical)
N	Number of load (stress) exceedances
n_x, n_y, n_z / N_X, N_Y, N_Z	Load factors along longitudinal, lateral, and normal axes respectively
P_{E_L}	Probability of exceeding load
$P_{E_L}(x_i)$	Load distribution function
P_{E_Ω}	Probability of exceeding the omega condition
$P_{E_{ULT}}$	Probability of exceeding ultimate load (strength)
P_{F_K}	Probability of failure during a finite time period
$P_{F_{LIM}}$	Probability of failure at limit condition or less
$P_{F_{TOT}}$	Total probability of failure
P_{RS}	Residual strength probability function during a finite time period
P_S	Probability of survival
P_{SK}	Probability of survival during a finite time period
$p_1(x_i, x_j)$	Probability density function for a structural system whose mean is x_j
$p_3(x_j)$	Probability density function of analytical error
q, Q	Dynamic pressure

RPO	Rolling pullout maneuver
R/t	Ratio of radius to skin thickness of a shell structure
SCF	Stress concentration factor = K_T
SDC	Structural design criteria
SPU	Symmetrical pullup maneuver
S.R.	Structural reliability
$S.R._{GOAL}$	Structural reliability goal
STRREL	Static strength, time independent, structural reliability computer program
s	Scatter factor on fatigue life
σ_{RS}	Residual strength stress
σ_S	Standard deviation in strength
σ_{ULT}	Ultimate stress
σ_{x_j}	Standard deviation in strength
TFS	Test factor of safety
V_e	Equivalent airspeed
V-G-H	Velocity, load factor, altitude recorder
V_H	Level flight high speed
V_L	Design limit airspeed
v_s	Landing sink speed

W_j	Landing gear jig drop test weight
x_{dp}	The design point
x_i, x_j	Integration or step intervals in load or strength distributions

The International System of Units (SI) was adopted by the Eleventh General Conference on Weights and Measures, Paris, October, 1960, in Resolution No. 12, Reference (32). Conversion factors for the units used herein are given in the following table:

CONVERSION FACTORS

To Convert from U.S. Customary Units	Multiply By	To Obtain SI Units
Degree	0.017453292519943	radian
Foot	0.3048	meter
Foot^2	0.09290304	meter^2
Foot/Sec^2	0.3048	meter/second^2
Free fall, Standard(g)	9.80665	meter/second^2
Inch	0.0254	meter
Inch-pound	0.011521246198	meter-kilograms
Knot	0.514444444	meter/second
Pound force	4.4482216152605	newton
psf	47.880258	newton/meter^2
psi	6894.7572	newton/meter^2
psi	6.8947572	meganewton/meter^2

SECTION I

INTRODUCTION

The development of a new procedure for defining quantitative structural design criteria by statistical methods is described in this report. This procedure is intended to overcome the problems associated with other structural design criteria procedures. These other systems were evaluated and the problems discussed in Volume I of this report. Volume III formulates and describes two computer programs used in this volume for conducting parametric studies of the effect of various parameters on structural reliability.

In order to develop a rational procedure, it is necessary to have a clear understanding of what the procedure is expected to accomplish. This understanding involves recognition that structural design criteria (SDC) does not stand isolated from all considerations except those explicitly affecting the structural system. SDC is only one part of the structural design system that produces a new structural system. This structural system is one of many subsystems which are part of a vehicle system. Many of these other subsystems interact with the structural system. These interactions constitute part of the environment of the structural system. The vehicle system becomes part of an operational system which provides another part of the structural system environment.

The basic philosophy of the new procedure is presented in Section II of this report. It is noted that the making of decisions is the key element in the procedure. There must be a decision as to what the structural system is expected to do. This must be followed by a decision as to whether the structural system will accomplish what it is intended to accomplish. These decisions become part of a decision network outlined in Section IV of this volume.

The various decisions must be based on information quantitatively defining what it is desired for the state of the structural system and what the actual state of the system is. This method of presentation is based on a concept presented by Draper.[1] Application of Draper's concept to the definition of a structural design system is described at length in Volume I.

This new procedure represents a modification of the Present (Factor of Safety) Structural Design System which was described and evaluated in Volume I. The procedure is a statistically-based, deterministic system in contrast to the Purely Statistical Structural Reliability Systems described and evaluated in Volume I. The design conditions in the new system are defined with the intent that they satisfy specified statistical considerations. However, once the decision is made, the design conditions become discrete conditions that define the structural requirements explicitly. These discrete conditions also define the interfaces with other systems. The areas of responsibility and nonresponsibility for both the structural and nonstructural systems can be established unequivocally.

The choice of these design conditions is based on a prediction of what is *expected* to happen in the future from knowledge of what has happened in similar circumstances in the past together with an analysis of expected modification of these past statistics. Where sufficient statistics are not available, engineering judgement is accepted as a form of prediction. The new procedure recognizes that the future results can be influenced or even controlled so that the statistics of actual future operations of the new vehicle can be forced to be consistent with the initial predictions in most cases.

Whether the structural environment can be controlled or whether it is noncontrollable, the results of the vehicle operations in the environment can be monitored. This information becomes part of the structural design system and is used to decide whether the operations and structural reliability attained are satisfactory. If not, a decision can be made either to change the actual operations to match the specified capability of the structural system or to change the specified structural capability to match the actual operations.

Section II develops the philosophy and rationale behind the new procedure. Section III presents the technical approach of the procedure. Section IV contains flow diagrams to illustrate the interaction of the various functions involved. Section V contains a synopsis of the procedure for quick assimilation of the salient features of the new approach. Application of the new procedure is demonstrated on the F-100 airplane in Section VI by comparing the output of the computer program with actual service records. Some of the advantages and some of the potential problems that may be encountered in implementing the new procedure are discussed in Section VII. Conclusions and recommendations are presented in Section VIII.

It is possible that the reader may desire an overview of the new procedure prior to starting to follow the development in Section II of the philosophy behind the new procedure. If so, it may be advantageous to read the brief step-by-step outline of the procedure in Section III or the synopsis in Section V. A one-page summary is presented on page 122.

SECTION II

THE PHILOSOPHY OF STRUCTURAL DESIGN CRITERIA

2.1 GENERAL

The purpose of the study, reported in this volume, is to accomplish the research needed to develop quantitative structural design criteria for aerospace vehicles. The criteria are expected to relate the probabilistic nature of design, operational, and environmental experiences to the structural performance.

In order to formulate a new procedure for structural design criteria (SDC), it is necessary to have a clear understanding of what the procedure is expected to accomplish. This section of the report will be devoted to that task.

The first step in the process of defining the purpose of SDC is to understand the relationship of SDC to the total structural design system. This question was taken up at length in Volume I of this report, but some of it bears repeating in order to establish the framework for the formulation of the new procedure. A structural design system is defined very broadly in this report. It includes far more than just the structural design criteria. It includes the state of the art affecting strength and loads analysis. It includes the drafting room procedures that affect the checking of the structural drawings. It includes the government material specifications and it also includes the know-how of materials producers. It includes fabrication techniques in the shop and it includes maintenance techniques in the field. It includes the pilot's flight handbook and it includes everything that has an interface with the structural system (commonly called the airframe or the hardware), and everything that has a bearing on whether the structure survives in the performance of its stated mission.

It is recognized that such a broad definition of the structural design system is not universally accepted. It is acknowledged that there are jurisdictional problems in any organization that inhibit control by the structures organization of all things that affect the structural system. Nevertheless, it is necessary in any evaluation of a structural design system to recognize the existence of these problems. One measure of the effectiveness of a system is how well it copes with these interface problems. Therefore, the approach developed in this report will not be limited by any preconceived ideas limiting the prescribed field of responsibility for the structures organization.

The philosophy to be followed in the development of the proposed new structural design criteria is described in several steps. First, the objectives to be accomplished by the SDC are defined. This corresponds to establishing the Desired State shown on Figure 1. Then, procedures to implement these objectives will be described. Finally, a discussion of what constitutes proof of compliance with the objectives will be presented. This corresponds to a determination of the Actual State as shown on Figure 1.

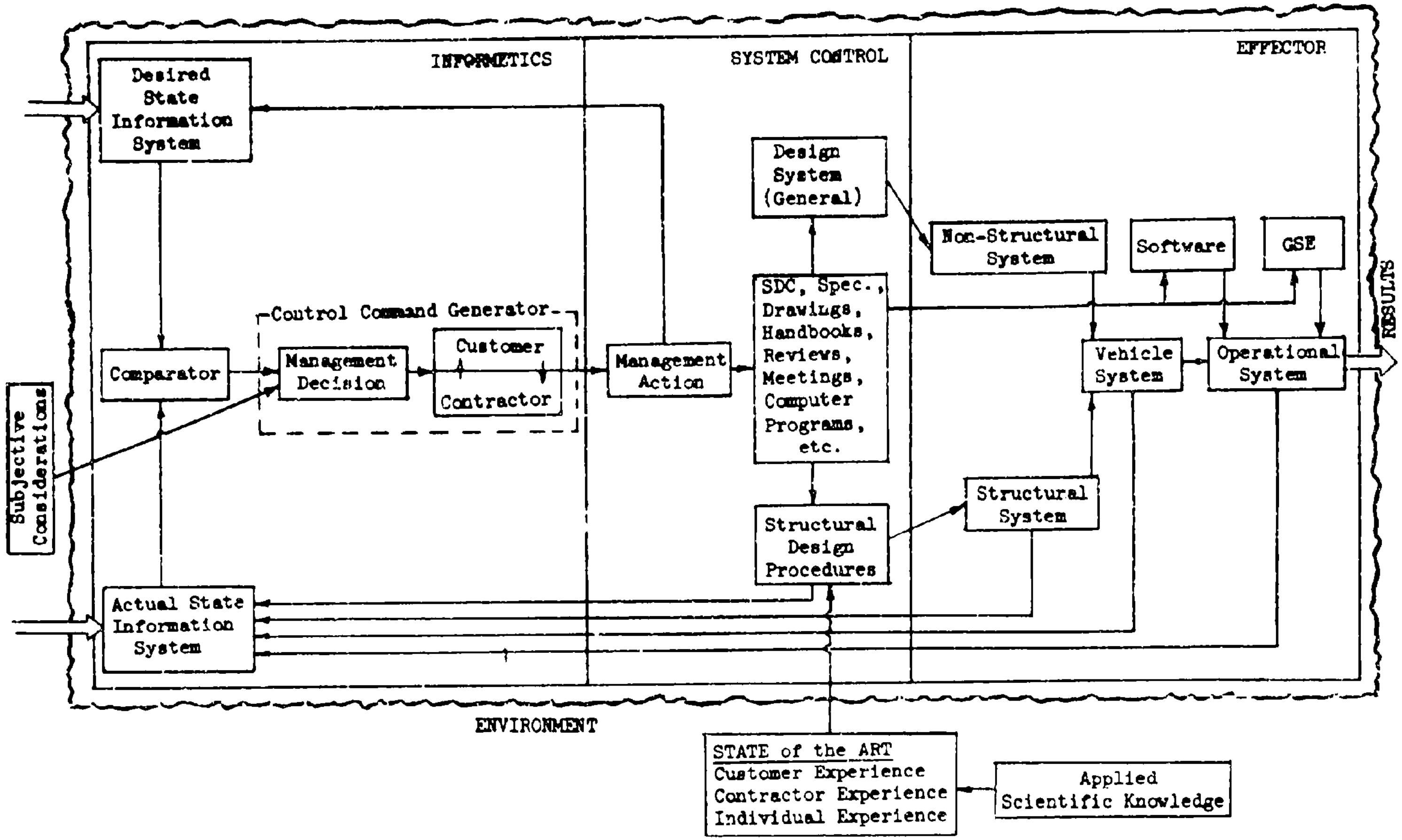


FIGURE 1. GENERALIZED FUNCTIONAL DIAGRAM — STRUCTURAL DESIGN SYSTEM

Although the basic philosophy set forth in this report is universal in its application, it is convenient to develop and discuss the philosophy first in terms of the simpler time-independent (static) strength situation. Then, it is extended to include the time-dependent situations such as fatigue, hot structure and erosion.

2.2 FUNCTIONS OF A STRUCTURAL DESIGN SYSTEM

A generalized functional diagram of a structural design system was presented in Volume I of this report. This diagram is reproduced as Figure 1 in this volume.

The fundamental purpose of any structural design system is the creation of an operational structural system that will enable the vehicle to satisfactorily perform its mission. The desired structure is not wished into existence. It is the result of many management decisions that trigger actions in many processes leading to the final product. The making of decisions is the key element in the procedure.

It should be noted from Figure 1 that Structural Design Criteria (SDC) is only one of the many functions that compose the structural design system. This serves to emphasize the fact that SDC, in and of itself, cannot guarantee a high level of structural integrity or structural reliability in any structural system. Many other considerations enter into the picture. As noted above, the purpose of a structural design system is the creation of an operational structural system that will enable the vehicle to satisfactorily perform its mission. This definition requires the specification of a number of functions before it is meaningful. It indicates that the vehicle has a mission to perform which, in turn, indicates that the structural system, as a vehicle subsystem, has a mission to perform. In order to determine if the structural system is performing its mission satisfactorily, the mission must be carefully defined and a quantitative definition of what constitutes satisfactory performance must be established. However, the simple act of defining the requirements for the structural system is not sufficient. As Coutinho[2] says, "There are individuals who believe that the specification is the end product; they are not concerned with hardware.... There was no appreciation either of what had to be done in the design and development cycle to obtain this level of reliability, or what reasonable level of reliability was needed to accomplish a mission."

The making of decisions at various times in the design procedure is the key element. The standard for judging the value of any structural design system must be the consideration of how effectively decisions are made and implemented. In Volume I the decisions to be made are grouped in three categories:

1. How effectively does the structural design system define the Desired State of the structural system?

2. How accurately can the Actual State of the structural system be determined?

3. How early in the design and deployment cycle of the operational system will any discrepancies between the Desired State and Actual State be disclosed?

Although the three questions above are phrased in the language used by Draper[1] (partially reproduced in Volume I), the questions are simply common sense. If a quantitative SDC is to be developed, one must decide what the structure is expected to do. This includes what the structure is not expected to do in terms of tolerating and surviving malfunctions, errors, and extreme or abnormal operational situations imposed on the structural system by non-structural systems. The decision on what the structural system is expected to do must be followed by a decision as to whether the structural system will accomplish what it is intended to accomplish. To make this decision it must be possible to measure or determine some function numerically in order to compare it with the desired value. If the number is equal to or better than the desired value of the parameter, the structural system is acceptable. If not, the structural system is unacceptable and changes must be made. Finally, the decision to accept or change the structural system must be made as early as possible in the design and deployment cycle. It is always more economical to change a prototype structure than to make changes during the production phase. The most unacceptable changes that can occur are those that occur after the vehicle has been accepted for operational usage. Thus, the concern indicated by the last of the three questions posed above.

Volume I of this report has evaluated the Present (Factor of Safety) Structural Design System, a Purely Statistical Structural Reliability System, and the individual approaches recommended by 14 different authors. It is shown that all of these procedures are deficient either in defining the Desired State of the structural system or in determining the Actual State. The procedure developed during this study is intended to remedy the deficiencies noted in Volume I.

Volume I concludes that "The fundamental problem area in the Present System resides in the fact that there is no clearly identifiable, quantitative objective that the Present System is expected to satisfy." A factor of safety (FS), such as the commonly used 1.5 value, does not provide any consistent level of performance for the structural system. Due to non-linearities and other considerations, one vehicle with a 1.5 factor of safety might be able to attain 1.75 times the limit operational condition and another vehicle with the same factor of safety might attain only 1.25 times the limit operational condition. Such a situation is discussed in Reference 3. Even if a given FS results in the same operational capability relative to the specified limit conditions, the frequency with which operations exceed the available structural capability may vary grossly from one vehicle system to another. The difference in failure rates associated with these possible situations might be orders of magnitude. It is difficult to accept the rationality of a system that would permit such divergent performances for vehicles expected to perform the same mission.

Most of the authors of the papers evaluated in Volume I of this report have adopted a system where a structural reliability number would be established as the requirement. The evaluation in Sections III and IV of Volume I has made

clear that such systems are not practical for the design of aerospace vehicles. The principal deterrent to the adoption of a Purely Statistical Structural Reliability System is the fact that there is no procedure for accurately determining the actual structural reliability of a particular structural design. As a result there is no proof of compliance technique that would be satisfactory for demonstration that a contractual requirement has been fulfilled.

2.3 TIME-INDEPENDENT (STATIC) STRENGTH SITUATIONS

The approach suggested in this report is intended to overcome the problems noted in Section 2.2. The logic of a very rudimentary system is developed in this section and then expanded step-by-step until it includes all of the elements of the real problem. This initial development of the approach has most of the attributes of the final system but the principles involved should be easier to comprehend in this simpler form. The complete approach is considered to be a modification of the Present (Factor of Safety) Structural Design System. The modifications will not require a radical departure from present standards for designing the structural system of an aerospace vehicle. However, some detail changes will be necessary to implement the new procedure. These changes will be noted as the development of the procedure unfolds.

The first simplification used in the presentation of the new procedure is to consider only situations where the strength of the structural system does not vary significantly during the life of the vehicle. This is the basis on which most of the present SDC have evolved. The functional model representing this type of structural system is obviously much simpler than the model for a system with a time-dependent strength. However, the basic principles involved in the development of the philosophy are not affected by the question of the time-dependency of the strength.

a. Rudimentary System

(1) Criteria

The philosophy on which the new procedure is based starts with recognition of the underlying desire to have no failures, ever, in the structural system. It is a verity which many authors have pointed out that a "no-failure-ever" requirement would result in an infinitely strong and infinitely heavy structure. Something less must be accepted. This could be called a "no-failure-unless" requirement. It simply is not feasible to require that a structural system support <u>any</u> conceivable load that might be imposed on it. Nor is it feasible to require that a structural system retain sufficient strength to survive with the understrength resulting from <u>any</u> conceivable error in design, fabrication or maintenance.

Following this line of reasoning, the first qualification to the "no-failure-ever" requirement is that no failures will be tolerated <u>unless</u> the vehicle is operated outside the defined and expected boundaries of the prescribed mission by a significant increment. Obviously, this requires a

careful definition of the mission and of these boundaries. It also requires a definition of what consitutes a significant increment beyond these boundaries. It should be noted that structural failures are never "acceptable" but may be tolerated as an unavoidable result of obtaining a minimum weight and, thus, a useful vehicle.

This suggests that the Desired State for the structural system could be qualitatively defined as follows:

> No structural failure will be tolerated while the vehicle is performing normally but failures during abnormal operations will be tolerated.

A more precise definition of normal and abnormal operations will be given later. Associated with this definition of when structural failure will or will not be tolerated should be a determination of who will be responsible in case a failure does occur. If responsibility can be assigned after a failure occurs, certainly responsibility for preventing failure can be allocated before a failure ever occurs. It is considered that this explicit assignment of responsibility is a vital element in the new procedure. It is something that is missing from the present procedures and from those procedures evaluated in Volume I.

As a specific example of the meaning of this principle of the allocation of responsibility for the prevention of structural failures, the definition of the Desired State given above can be expanded to include a definition of responsibility. The structural system and those concerned with its design, fabrication and maintenance are responsible for the prevention of structural failures while the vehicle is operating normally. On the other hand, they are not responsible for failures that occur while the vehicle is operating abnormally. Since structural failures will be tolerated if they occur in the range of operations considered to be abnormal, it must be the responsibility of the non-structural systems to prevent failures in this range by avoiding the abnormal situation.

To develop a definition of the normal range of operations where the structure is expected to never fail and the abnormal range of operations where structural failure will be tolerated, the capability to distinguish between a normal and an abnormal operation must be developed. It does not appear to be reasonable to consider that operations at some particular level of severity are normal whereas operations at an infinitesimally more severe condition are abnormal. However, it does appear reasonable to designate one level of operation as normal and another at a discretely higher level as abnormal.

If the structural system had characteristics, such that it "never" failed at the operational level designated normal, but "always" failed exactly at the level designated abnormal, the system would meet the definition for the Desired State of the structural system given above. This hypothetical system has some interesting attributes. If the structural system "always" failed at the level designated as abnormal, it would "never"

fail at the level designated as normal. This would fulfill the responsibility of the structural system to prevent failures under normal operational conditions. Failures would occur whenever the level designated as abnormal was exceeded. However, responsibility for preventing such failures is outside the purview of the structural system. Failures would occur only if the abnormal operation is encountered. Responsibility for prevention of such abnormal operations and thus prevention of structural failures as a result of such operations rests with those responsible for the vehicle operation.

This description of the proposed structural design system is essentially a description of the Present System that has evolved in the design of aerospace vehicles during the years past. The normal operating conditions have been called limit conditions. These limit conditions have been conveyed to operating personnel by handbooks describing operational limitations for the vehicle, by placards and by other means. Operations up to the limit conditions are permissive and, thus, must be considered normal. Any structural failure at limit condition or less is not considered tolerable and structures that fail in such circumstances are almost automatically strengthened. Operations beyond limit are not approved so any substantial violation of the operational limitations must be considered an abnormal operation. Most failures of past structural systems, aside from those caused by correctable errors in the structure, have come from operations well beyond limit conditions. Such failures have to be the responsibility of the vehicle user and not the responsibility of the structural system. As long as such abnormal usage does not occur more often than is considered reasonable for the class of vehicle in question, the structural system is considered to be satisfactory.

This willingness to tolerate the relatively rare, infrequent structural failures that are the result of operating the vehicle abnormally—well beyond the limits of the prescribed normal operation—represents a qualification of the desire for a no-failure-ever situation. On this basis, the Desired State could be redefined as:

> No structural failure will be tolerated unless the failure is caused by an abnormal operation of the vehicle and provided that the abnormal operation occurs infrequently at a rate that is compatible with the mission of the vehicle.

At this stage in the unfolding of the philosophy guiding the development of the proposed new procedure, the model of the structural design system qualitatively has all the elements of a realistic, practical system. However, further qualifications will be added as the development proceeds. It will clarify this future development if the significance of the development to this point is restated. Two operational conditions are defined — a normal and an abnormal condition. The structure is expected always to survive the normal condition. Failure at the abnormal condition will be tolerated. The failure rate of the vehicle will correspond to the frequency of attaining the abnormal condition. The probability of structural failure will be equal to the probability of exceeding the designated abnormal condition. If a particular value of structural reliability is designated as the minimum acceptable, the complement of this structural reliability value represents the maximum

probability of failure that will be tolerated. In turn, this means that the probability of attaining the abnormal condition where the structure is expected to fail must be no more than the complement of the desired structural reliability value. Then, it follows that, if the operational condition that is designated as abnormal is chosen initially so that its probability of exceedance is equal to the complement of the desired structural reliability and if the structure is designed so it will always fail at or above this condition designated as abnormal, the desired structural reliability will be attained automatically.

(2) Responsibility and Administrability

The responsibility for implementing the requirement just stated can be divided into two separate, identifiable requirements. One would be the responsibility of the structural system and the other would be the responsibility of the operational, or nonstructural, system. In effect, this procedure decouples the two systems and permits the requirements for each to be specified separately. A pair of numbers representing the definition of the normal and abnormal condition would be common to the requirements for each system. Once these numbers were established, they would not be dependent on the procedure by which they were established. They would stand by themselves with the effect of a specification requirement.

The structural system would have the obligation to fulfill two requirements. One would be to provide the operational vehicle with a structural system that would always fail exactly at the operational condition designated as abnormal. (Remember that this discussion is still for a hypothetical design, much simplified from the true situation.) The second structural requirement would be to never fail at the condition designated as normal. This second requirement is met automatically if the first requirement is met. So the structural requirement at this point reduces to a requirement to survive the "abnormal" condition. It is pertinent to note that this requirement is very similar to but not identical with the requirement in the Present (Factor of Safety) Structural Design System. In the Present System the structure is required to survive ultimate loads, defined as limit loads multiplied by the factor of safety. In the new procedure the structure is required to survive the operational condition designated as abnormal. This means that the structure must survive the loads associated with the abnormal condition. So both procedures require that the structure survive a single, discrete set of loads, although the loads may be different in the two systems.

Such a requirement is an administrable requirement. If a contract is written on the basis of this procedure, the requirements can be defined easily. The contractor must provide a structural system capable of surviving the condition designated abnormal. This condition is a discrete condition, identifiable by a number (a set of numbers). If the structural system fails at less than this specified condition, the contractor has not fulfilled his obligation. On the other hand, the contractor has no obligation to provide any more structural capability than the absolute minimum necessary to survive the specified condition. Thus, the contractor's obligations are specific but limited which is the basis for an administrable requirement.

The decoupling of the structural and operational requirements imposes some obligations on the operational system and the vehicle user. The definition of the two operational conditions, normal and abnormal, delineates these obligations of the vehicle user. The normal condition is by definition just that. The user should be free to operate up to this condition since the structural system has the absolute responsibility for preventing structural failures in this operational range. Beyond this specified normal condition, operations are not considered to be necessary to the performance of the vehicle mission. It is recognized that occasional operations beyond the condition designated as normal may occur. However, if any operation is so far beyond the normal condition that the condition designated abnormal is exceeded, the structural system may fail. The responsibility for this operation and the subsequent failure must be accepted by the vehicle user.

As with the requirements for the structural system, the requirements for the operational system are similar to but not identical with those in the Present (Factor of Safety) System. The Present System establishes a limit condition that is comparable to the condition designated normal in this dicussion. It is a condition representing the upper limit of the permissible operational range in both procedures and one that is high enough so that all normal operations required by the mission can be performed without exceeding the specified condition. In this respect the two procedures are identical. There is no comparable condition in the Present System to the condition designated as abnormal in the proposed system. However, the actions of the authorities in past situations where the operational limitations have been grossly exceeded have been an implicit recognition that such operations are abnormal. There has been no explicit level where such a determination is made in advance. Nevertheless, it is inconceivable that, in any accident where the aircraft was known to exceed the operational limitation by 40 or 50 percent, the cause of failure would not be attributed to the user. The structural system almost certainly would be considered adequate in such a situation. The specification in advance of the operational level at which the structural system has no responsibility for survival and where the user is considered to have grossly overloaded the vehicle does not really change what has always been recognized after the fact. Therefore, the concept is not as radical a departure from past practice as it might seem to be.

To summarize, the structural system is expected to always survive the normal condition. If it doesn't, sole responsibility for the failure rests with the structural system since operations to this level are permissible. The structure is not expected to survive beyond the designated abnormal condition. If a failure does occur due to vehicle operation in this region, sole responsibility for the failure rests with the operating system.

With some additional definition of the exact meaning of some of the words used to describe the proposed procedure and with some additional minor qualifications on some of the requirements, the structural design system just described can serve as a rational, practical procedure for deciding what is required of the structural system and for administering compliance with the requirement.

(3) Criteria Terminology

The first term that must be defined more precisely is an operational condition. Generally, an operational condition is some parameter or combination of parameters that represents the state of the vehicle as a whole. An operational condition should be something physically meaningful to the vehicle user and generally controllable by the user. It should represent a definable interface between the engineer or vehicle designer and the vehicle user. Such functions as load factor, weight and velocity are certainly operational conditions. So also are control surface position and vehicle attitude. Typically, in aircraft practice they are functions the pilot can sense qualitatively even if instrumentation is needed to determine the function quantitatively.

Ordinarily, functions that are local to the structural system, such as wing root bending moment or the stress at the corner of a fuselage window, are not operational conditions. However, in certain instances, parameters of this type can be transformed into an operational condition by providing the pilot with instrumentation so he can monitor the value of the parameter at all times.

User-controlled conditions define most of the environment to which the structural system is exposed. However, there are some conditions imposed on the structural system by other vehicle subsystems. For instance, the pressure in a tank may be controlled routinely by an automatic regulating system with additional regulation against overloads provided by a pressure relief valve. The pressures as controlled by the regulating subsystem can be considered as operational conditions for the structural system. In the same vein, the mass and velocity of meteoroids impacting on a space vehicle are considered as operational conditions, even though they are not controllable by the user or by a non-structural subsystem. From here on in this paper, the term operational condition will include any environment or input imposed on the structural system by a non-structural system.

In establishing a requirement for the structural system to survive a particular operational condition, it is understood that failure occurs when the local load on the structure exceeds the local strength. The transfer function that transforms an external vehicle condition into an internal vehicle load may involve personnel from many disciplines, such as dynamicists, aerodynamicists and weights engineers. These are all included when speaking of the structural system. The basic interface is considered to be between the vehicle user and the vehicle designers.

The term load is interpreted very broadly in this discussion. It includes those functions that are conventionally thought of as loads, such as shear, bending moment and torque. It also includes local temperatures, vibration amplitudes and corrosive influences where they affect the failure potential of the structural system.

Another usage that needs defining is the concept of error. In the context of this paper, an error is anything where the final result is not as initially predicted. The reason for the discrepancy and the blame, if any,

are immaterial. An arithmetical blunder such as a decimal point error or transposing numbers is less defensible but has the same result as a discrepancy due to ignorance. The ignorance itself may be that of an individual who lacks some vital knowledge even though other knowledgeable individuals possess the requisite knowledge. Or the ignorance may represent the current state of the art with no one knowing the correct solution to some problem. The single term "error" covers all these considerations.

One final definition is needed in the discussion and development of a quantitative structural design criteria. This is the name of the operational conditions heretofore designated as normal and abnormal. The upper limit of the normal operational conditions has been considered to be a limit condition for many years. A limit condition may actually represent a combination of two or more parameters such as aircraft load factor and speed. Wave height, wave slope, wind velocity, and vertical impact velocity in combination might define a limit condition for the water landing of a space capsule. This meaning of a limit condition is consistent with the meaning currently attributed to the limit condition in the Present (Factor of Safety) Structural Design System.

The condition previously described as an abnormal operating condition has a new meaning. This condition corresponds to what some[4] have called an ultimate condition in the past. The term ultimate condition could be adopted in this discussion but experience has suggested a different name would be desirable. No matter how carefully it is explained that the loads for the ultimate condition do not represent exactly the same thing as the ultimate loads in the Present (Factor of Safety) Structural Design System, there always seems to be some confusion on this point. For this reason it appears desirable to adopt a new term for the abnormal operational condition that defines the condition where there is no further responsibility for structural survival. It is suggested that the term "omega condition" would be a useful term here. It would emphasize that the condition is separate and distinct from the limit condition, and it may be significantly different from the condition associated with the ultimate loads of the Present System. If desired, the reader can substitute "ultimate condition" for "omega condition" without changing the meaning of the discussion.

It is interesting to note that the concept of an ultimate or omega condition antedates the use in the Present System of the loads at limit condition multiplied by a factor of safety. The Wright brothers[3] designed their original airplane structure to support five times the weight of the airplane. This corresponds to designing for what is now called an omega condition. This practice was general in airplane design until about 1934 when the factor of safety concept was introduced into civil regulations.

b. Systems with Strength Scatter Considered

The assumption made in the previous sub-section that all the vehicles in the fleet failed exactly at the omega condition is equivalent to saying that there is no scatter in the strength. Statistically, the coefficient of variation in strength, γ_s, would be zero. Most structural systems for the aerospace systems of the past were relatively narrow in strength scatter. Although the structures and the structural design system did not make explicit

determinations of γ_s, the procedures were consistent with systems whose γ_s's were small — approaching zero. In Volume I it is pointed out that the structural systems of the future may be forced to use materials and configurations that will predispose towards larger values of γ_s. Therefore, any realistic procedure for quantitative structural design criteria by statistical methods must consider the effects of the strength scatter, γ_s.

It is part of the basic philosophy being developed in this section of Volume II that the structural system should be developed in incremental steps much as it is in the Present System. This means that strength is first calculated analytically for a set of analytically determined loads. Then, the strength is verified for the analytically determined loads. Next, the loads are verified for the specified operational conditions. Finally, the relation between the specified operational conditions and the actual operational experience is verified by appropriate means.

As a result, the structural requirements are based on the premise that, if the operational conditions are as specified, the structural performance must satisfy the desired level of structural reliability. Obviously, the reliability of the structural system and the vehicle system will be deficient even if the vehicle is properly operated, whenever the structure is incapable of surviving the loads associated with proper operation. Therefore, it seems appropriate to establish a structural design criteria that will provide, as a minimum, a structural system that will result in the desired level of structural reliability provided that the vehicle system is actually operated as it was predicted it would be operated. What to do if the operational results differ from the predicted results will be discussed later on.

The basis for design as just described corresponds to a conditional structural reliability. It has many advantages. It continues to implement the decoupling of the requirements for the structural and non-structural systems. It would seem reasonable that the definition of the limit and omega operational conditions — the normal and abnormal of operations — should be independent of any consideration of the type of structure that results from the design process. In other words, the user should be able to operate an airplane in the prescribed manner with expectation that the same structural capability is being provided whether there are forgings or castings in the wing, whether the structure is "hot" or "cold," or whether the wing leading edge is aluminum, beryllium, or graphite. Therefore, the operational requirement should be defined first and then adequate structure provided to meet the operational requirement. This is not to say that the initial desire for operational capability may not be modified if necessary to obtain a practical structure. In such a case, there should be an explicit agreement that the vehicle can and will be operated to more restrictive limitations.

With the philosophy established that it is desired to obtain a particular level of structural reliability given that the operational conditions meet specified requirements, it is possible to develop the next step in the procedure. Reference 5 proposed three levels for structural reliability objectives. These are reproduced herein as Table I. It is not suggested that these particular sets of figures must be adopted, but they are convenient to illustrate the procedure being developed.

TABLE I

STRUCTURAL RELIABILITY OBJECTIVES

	Standard Vehicles	Alternate Vehicles	
		Low Risk Vehicles	High Risk Vehicles
Structural Reliability Goal	0.9999	0.999999	0.99
Probability of Exceeding Limit Condition	0.01	0.001	0.1
Probability of Exceeding Omega Condition	0.0001	0.000001	0.01
Conditional Limit Reliability	0.999999	0.99999999	0.9999
Conditional Omega Reliability	0.99	0.99	0.99

If it is assumed that the probability of exceeding limit condition and omega condition will not be greater than specified on Table I, the structural reliability that will be attained provided that the structure meets its requirements can be determined. Load spectra corresponding to values of Table I are shown on Figure 2. The important point of these curves is that the probability of exceeding the omega condition is the complement of the desired structural reliability.

$$P_{E_\Omega} \leq 1 - S.R._{GOAL} \tag{1}$$

Then, it is assumed that the probability that the strength exceeds the omega condition is 0.99. This corresponds to the value on Table I. More important, this corresponds to what has been the practice in the Present System for years. In effect, the strength allowable is matched up with the omega load. Based on these assumptions the curves of Figure 3 are computed by the program described in Volume III. These curves show that, over a wide range of γ_s, the structural reliability will approximate the complement of the probability of exceeding the omega condition,

$$S.R. \approx 1 - P_{E_\Omega} \tag{2}$$

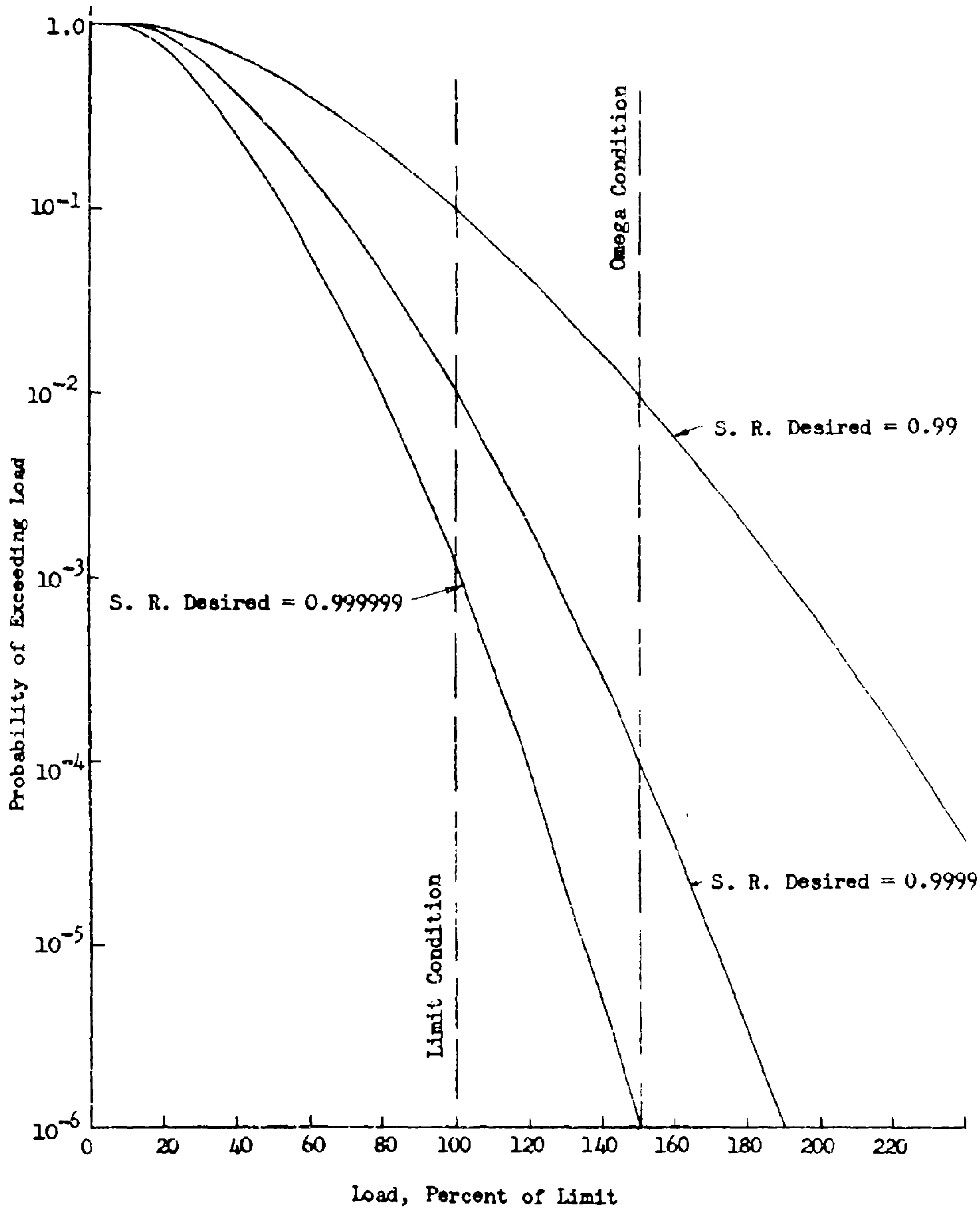


FIGURE 2. WEIBULL LOAD CURVES

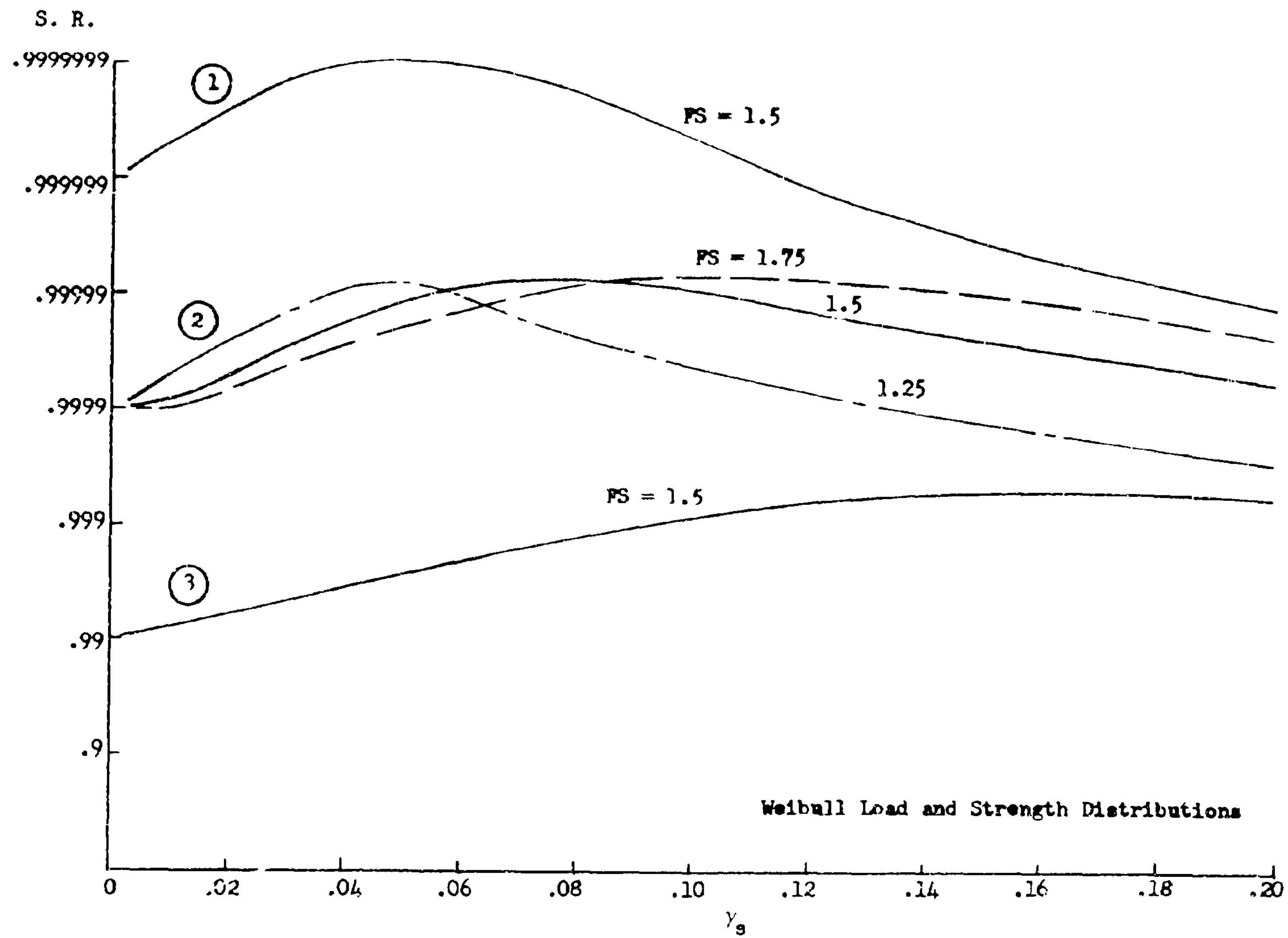


FIGURE 3. STRUCTURAL RELIABILITY WITH NO ERROR

provided that the allowable (99 percent exceed value) is matched to the omega condition. It should be noted that, at very large values of γ_s, the S.R. will approach 0.99, which is the same value used for the allowable.

The middle curve on Figure 2 has been modified on Figure 4 to show that the conclusions drawn in the preceding paragraphs are not too sensitive to the exact value chosen for the probability of exceeding the limit condition. Figure 4 shows two variations from the basic curve of Figure 2. The probability of exceeding omega is held constant at the prescribed value of 10^{-4}. The probability of exceeding limit condition is also maintained at the prescribed 10^{-2}, but limit is moved up and down in relation to the omega condition. This could be expressed in terms of factor of safety with the basic curve corresponding to a 1.5 F.S. The two alternate curves would be for 1.25 and 1.75 F.S. The corresponding S.R. curves are computed and plotted as the dotted lines on Figure 3.

From the added curves it is apparent that the shape of the loading spectrum does not have much effect on the general level of structural reliability attained. For the lower values of strength scatter, the level of structural reliability obtained is governed largely by the frequency of exceedance of the omega condition. It may seem obvious but it is important to develop an appreciation for this relationship. It is the basis for the concept that the omega condition can be established as a deterministic value together with the allowable as a single deterministic value. Then, if these two values are established properly, the structural reliability will correspond to the desired value automatically without the necessity for laborious and unprovable statistical calculations. At this point in the development, the procedure incorporates most of the features of the final system. These are summarized as follows:

A designated structural reliability level will be attained if

1. The probability of exceeding the omega condition is the complement of the desired S.R. $\left(P_{E_\Omega} = 1 - \text{S.R.}\right)$, and if

2. The allowable strength of the structural system is such that 99 percent of the individual structural systems exceed the allowable and the allowable strength equals or exceeds the load for the omega condition, and if

3. The coefficient of strength variations, γ_s, is small (i.e., $\gamma_s \leq 0.10$), and if

4. There are no mistakes or errors in the determination of the previous three parameters.

The last condition is the most important of the four, yet it has been completely overlooked in all previous work in this field. Volume I devotes considerable attention to this problem. It is noted that all of the procedures reviewed in Volume I make the implicit assumption that the load and strength distributions are known beyond any possibility of error. Past history, documented by Reference 6 and many other records, does not justify the

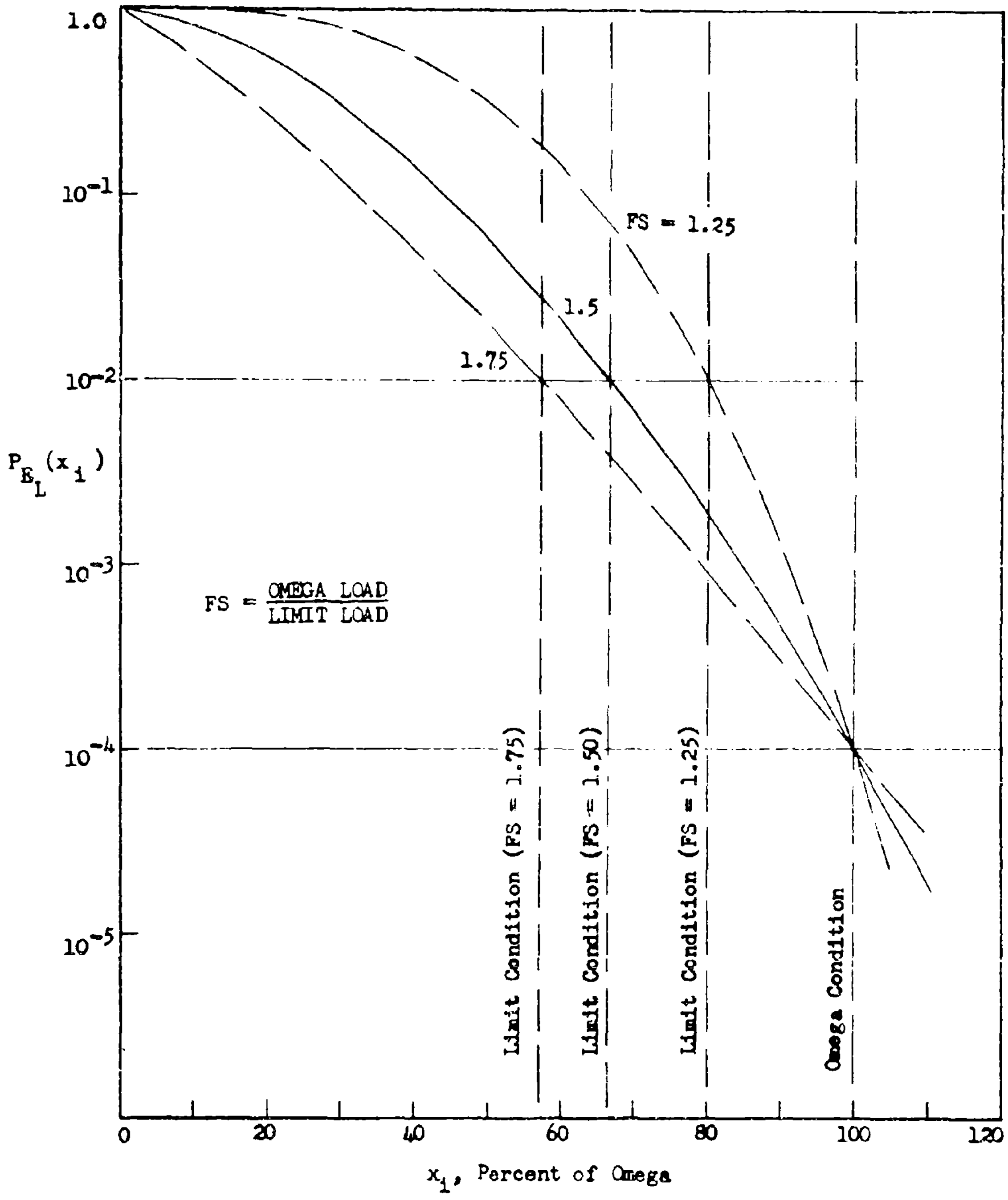


FIGURE 4. LOAD DISTRIBUTIONS

no-error assumption. As a result, the calculated S.R.'s presented on Figure 3 cannot be considered to be realistic. They will be true only if errors were never made in the various analyses involved in the computations. Accordingly, this no-error assumption cannot be used as the basis for a rational procedure. Therefore, the question of the possibility of analytical errors in the strength analysis will be taken up in the next section.

c. Systems with Analytical Errors Considered in the Strength Analysis

The previous section developed the procedure beyond the rudimentary system of Section 2.3a by considering the effect of strength scatter on the structural reliability. The section concluded that the procedure, as it stood, was not realistic because of the assumption that there were no errors in the loads and strength analyses. It was noted that Reference 6 and other sources have documented the fact that there have been many structural failures in strength tests at load levels considerably below the predicted level. Figure 5 presents data from Reference 6 showing the frequency with which structures fail at less than the intended design load. There is every evidence that the incidence of analytical errors today has not changed significantly from that presented on Figure 5. If this is true, the S.R. obtained by analysis alone will be dominated by the error effect. Figure 6 shows this effect. Curve (2) on this figure shows that no matter what the probability of exceeding the omega condition, the resulting S.R. is very low (approximately 0.9). The spread in results on Curve (2) results from assuming variations, described in connection with Figure 17, corresponding to better or worse analytical accuracy than that of Figure 5. Figure 7, reproduced from Volume I, shows that no matter what the coefficient of strength variation, γ_s, the attained S.R. will be in the vicinity of 0.9 when the error function is included in the determination of S.R. Both Figures 6 and 7 show that sizable changes in the error function from that of Figure 5 make relatively little difference in the attained S.R. Thus, it must be concluded that the simple fact that analytical errors are made far overshadows all other considerations in determining the true structural reliability of structural systems designed solely by analytical techniques. Accordingly, the next step in developing a procedure for quantitative structural design criteria by statistical methods must be to recognize that analytical errors will occur and to expand the procedure to consider the statistics of these errors and how they affect structural reliability. The computer program described in Volume III includes the analytical error function as an integral part of the program. The philosophy followed in developing this computer program is rather straightforward in terms of the functions already discussed in the previous sections of this report. The logic of the procedure continues to be developed in the framework of Professor Draper's[1] informetics concept as described in Volume I.

The Actual State of the structural reliability of a particular model or design can never be known precisely if it is acknowledged that errors do occur in the strength analysis. If two new designs are considered at the same time, one model may actually have the predicted strength and have a very high S.R. The other model may have an error in the predicted strength and have a very low S.R. Which one has the error and which one is error-free cannot be determined on the basis of the analysis alone. Obviously, if it

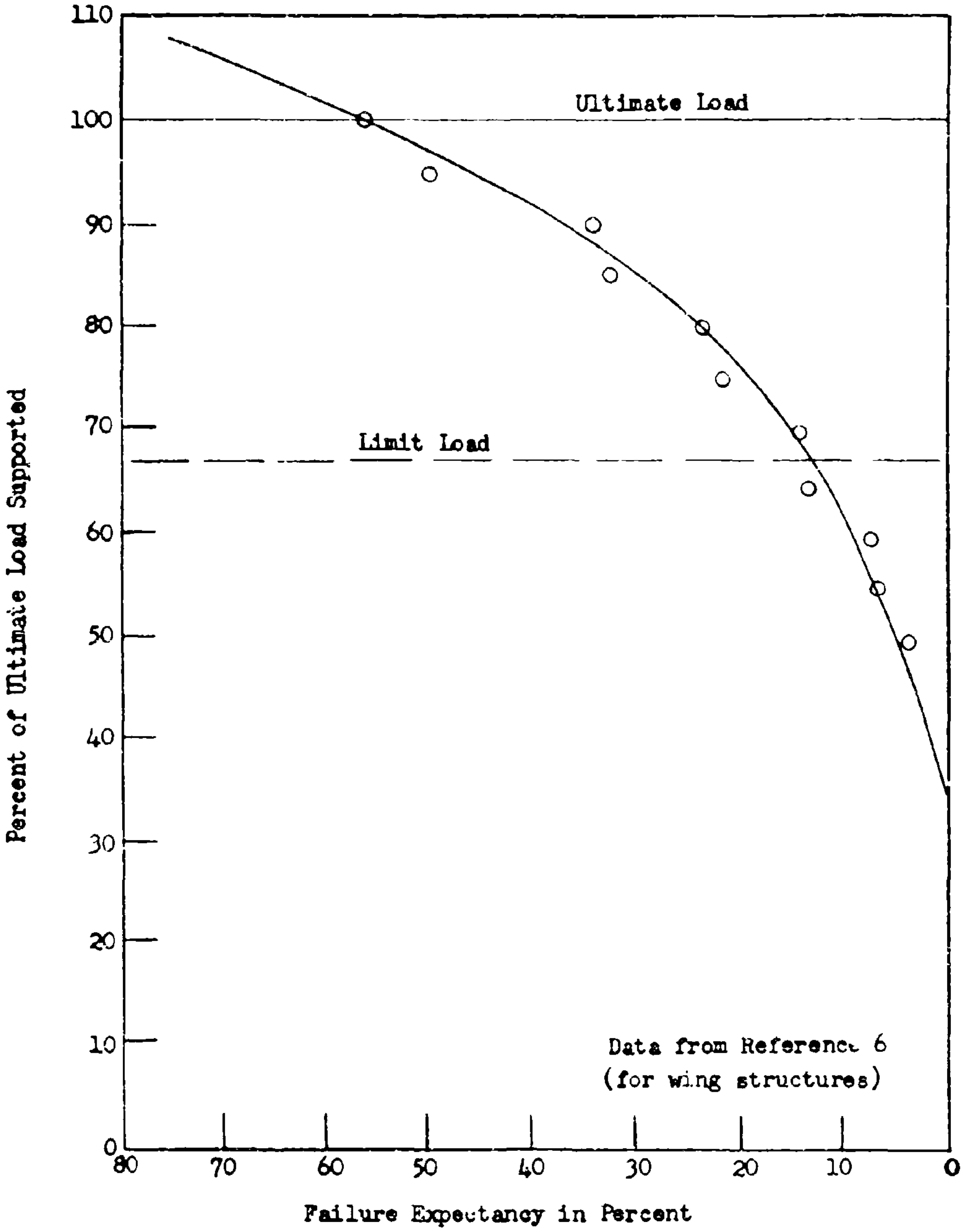


FIGURE 5. FAILURE EXPECTANCY IN STRUCTURAL TESTING

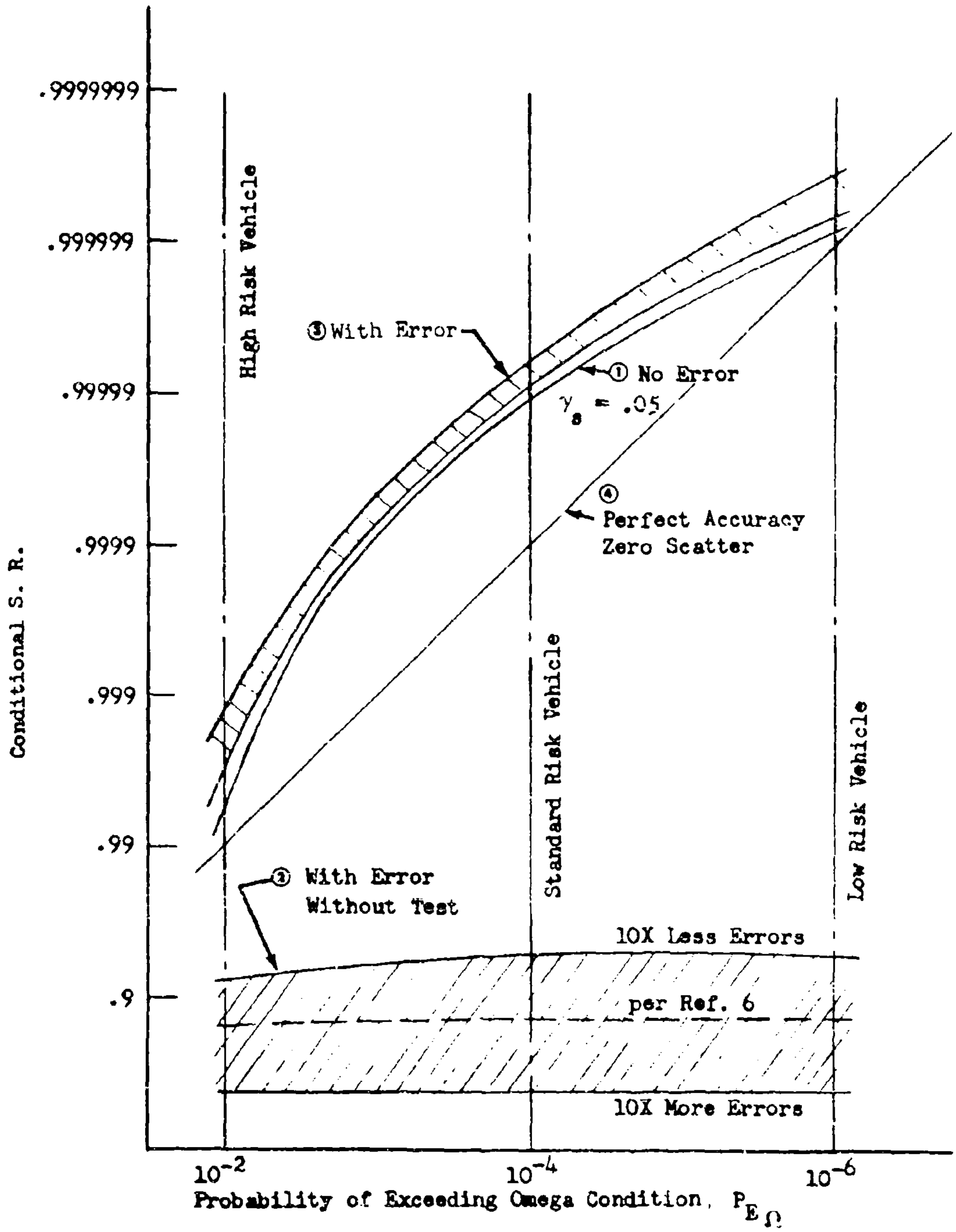


FIGURE 6. EFFECT OF ERRORS AND TESTING ON STRUCTURAL RELIABILITY

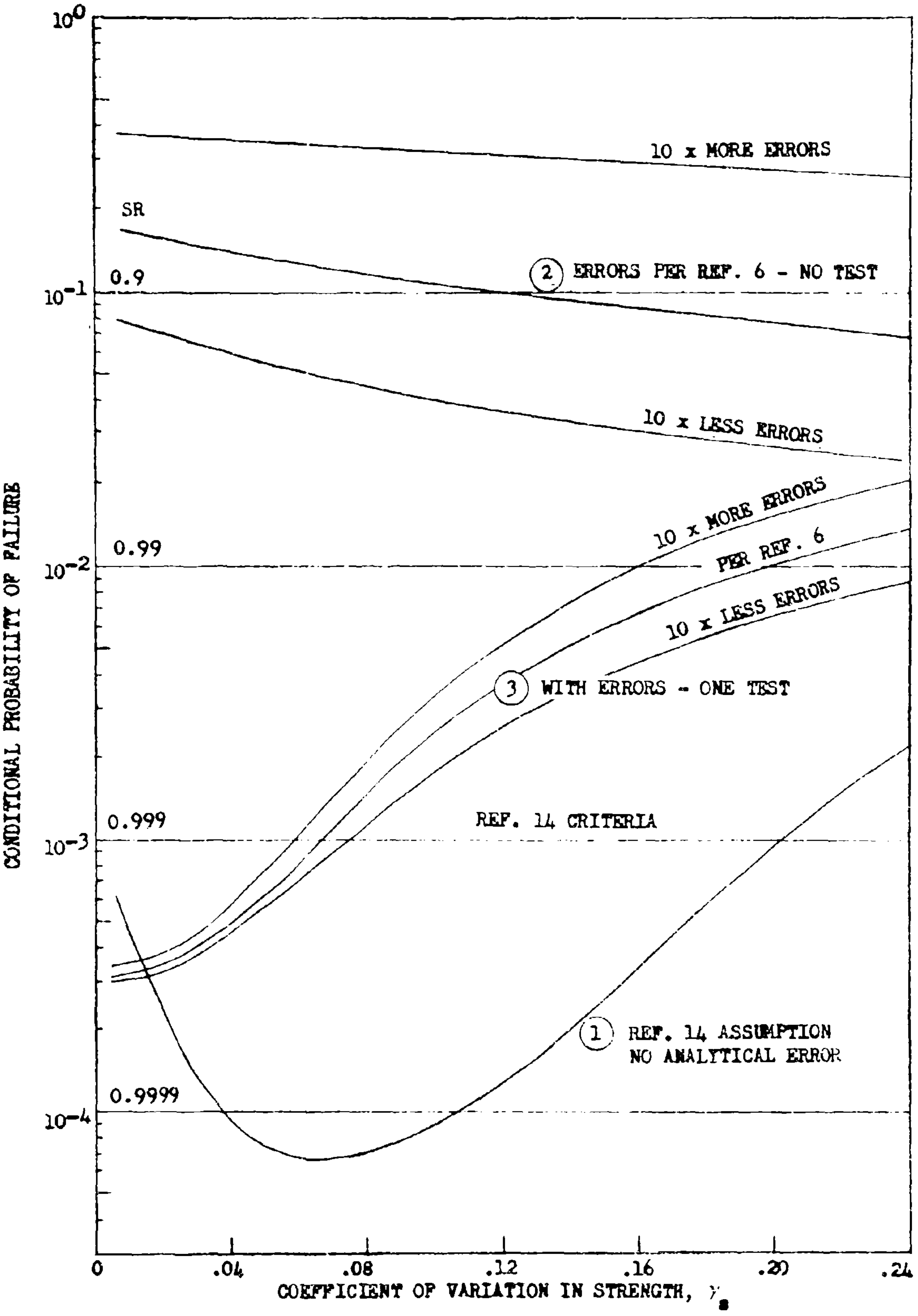


FIGURE 7. PROBABILITY OF FAILURE VERSUS γ_s FOR AUSTIN'S CRITERIA

were known that one of the models incorporated an error in the design, the error would be corrected and that design would then be error-free. The data of Figure 5 shows that approximately one out of every ten designs has a strength that is two-thirds of the intended design strength or less. From this it can be concluded that out of every 100 new designs, ten will have a strength level less than the two-thirds value. But which ten cannot be determined on the basis of the analysis alone. However, it can be concluded that a brand new design has a one-in-ten chance of failing at two-thirds of the load for which it was designed. This reasoning is carried out in the program presented in Volume III for the possible range of error magnitudes and the probability with which they will occur. The program is described in detail in Volume III, but the philosophy of the approach is outlined here.

First of all, it is accepted that the probability of a test failure from Reference 6 as shown on Figure 5 represents the probability of making an error in the strength analysis of a given magnitude. This implicitly assumes that all of the premature failures described in Reference 6 were due to discrepancies in design rather than discrepancies in fabrication. This is not quite correct, but examination of Reference 6 indicates a large majority of the failures were caused by design errors. Rather than attempting to determine the exact value of the failures attributable to design errors (which value would be subject to challenge with each different organization involved and each change in technology considered), it is shown later that the computed results are not very sensitive to the specific error function assumed.

A mathematical expression is presented in Volume III approximating the empirical function shown on Figure 5. The derivative of this function is the probability density function of analytical error. This derivative of the error function is

$$p_3(x_j) = 3.718\ x_j^{2.718}/(x_{dp})^{3.718} \qquad (3)$$

In this equation, x_j is the randomly distributed location of the mean strength, and x_{dp} is a "design point," which is derived from the error data in Reference 6. The value for x_{dp} used in the computer program described in Volume III is 1.06796 μ_T, where μ_T is the theoretical mean strength associated with a specified allowable, the fraction of the structures that exceed the allowable and the coefficient of strength variation, γ_s. Simply stated, this function $\left[p_3\ (x_j)\right]$, multiplied by the width of the integrating interval being used, represents the fraction of the new designs whose mean strength will be in the interval x_j to $x_j + \Delta x_j$ when the intended design strength was close to the design point x_{dp}. In the analysis it would be calculated that the "allowable" strength (usually the 99-percent-exceed strength) was equal to the required strength. The probability density function (Gaussian) for a structural system whose mean is x_j can be written as

$$p_1(x_i, x_j) = \frac{1}{\sqrt{2\pi}\sigma_{x_j}} \exp\left\{-\frac{1}{2}\frac{(x_i - x_j)^2}{\sigma_{x_j}^2}\right\} \qquad (4)$$

The probability that the particular system whose mean is x_j will fail in the interval $x_i + \Delta x_i$ can be written

$$\Delta p_{25}(x_i) = p_1(x_i, x_j)\, p_3(x_j)\, \Delta x_j \Delta x_i \qquad (5)$$

Qualitatively, the situation can be clarified by a sketch showing the relationship involved. From equation (3) it can be calculated that 2.4 percent of the systems intended to have their design strength at 150 will actually have the mean between 95 and 105. Of those 2.4 percent whose mean is in the 95-105 interval, 6.1 percent will fail in the interval from 75 to 85. This determines that the probability that the mean of the group is between 95 and 105 and that one particular vehicle from the group will fail in the interval 75 to 85 is 0.024 x 0.061 = 0.00146. Since it is not known where the mean really is, the possibility that the mean might be at any value of x must be considered. For instance, Figure 8 shows that 4.38 percent of the designs will have their mean strength from 120 to 130. The probability that an individual article from this group will fail in the interval 75 to 85 is 0.00066. Then, the probability that the mean will be at 125 and have a failure at 80 is 0.0438 x 0.00066 = 0.00003. Now, the probability of failure at 80 from these two possibilities is 0.00146 + 0.00003 = 0.00149. To get the total probability, the integration must be performed over the whole range of possible x_j's, not just the two used for the illustration.

It must be understood that any one vehicle system cannot have its mean strength at all of the infinity of the possible values as might be thought when the procedure integrates over the whole range of possible x_j's. Each particular vehicle system has a particular value of mean strength associated with that system. But the particular value is unknown. Therefore, it must be considered that there is a chance that the mean strength is at any of the values. Thus, equation (3) expresses the probability that the actual value of the unknown mean is at x_j. The integration of the product of the chance that the mean strength is at x_j and the chance that an individual vehicle strength is at x_i represents the probability that, in a complex of systems as described in Section 3.4 of Volume I, an individual vehicle will fail at x_i. Since the statistical parameters for the individual system are not known, equation (5) represents all that is known about a newly-designed structural system after the design is complete but before any strength tests or operational data are available.

A slightly different description of the problem of defining the S.R. of a new design may be useful in developing an understanding of the effect of analytical errors on the S.R. Figure 9 shows a representation of the initial (before test) strength distributions on a hypothetical group of different structural systems. These systems from A to T could be thought of as typical structures designed by various contractors for various different vehicle models. The strength of all of the designs was intended to be as indicated

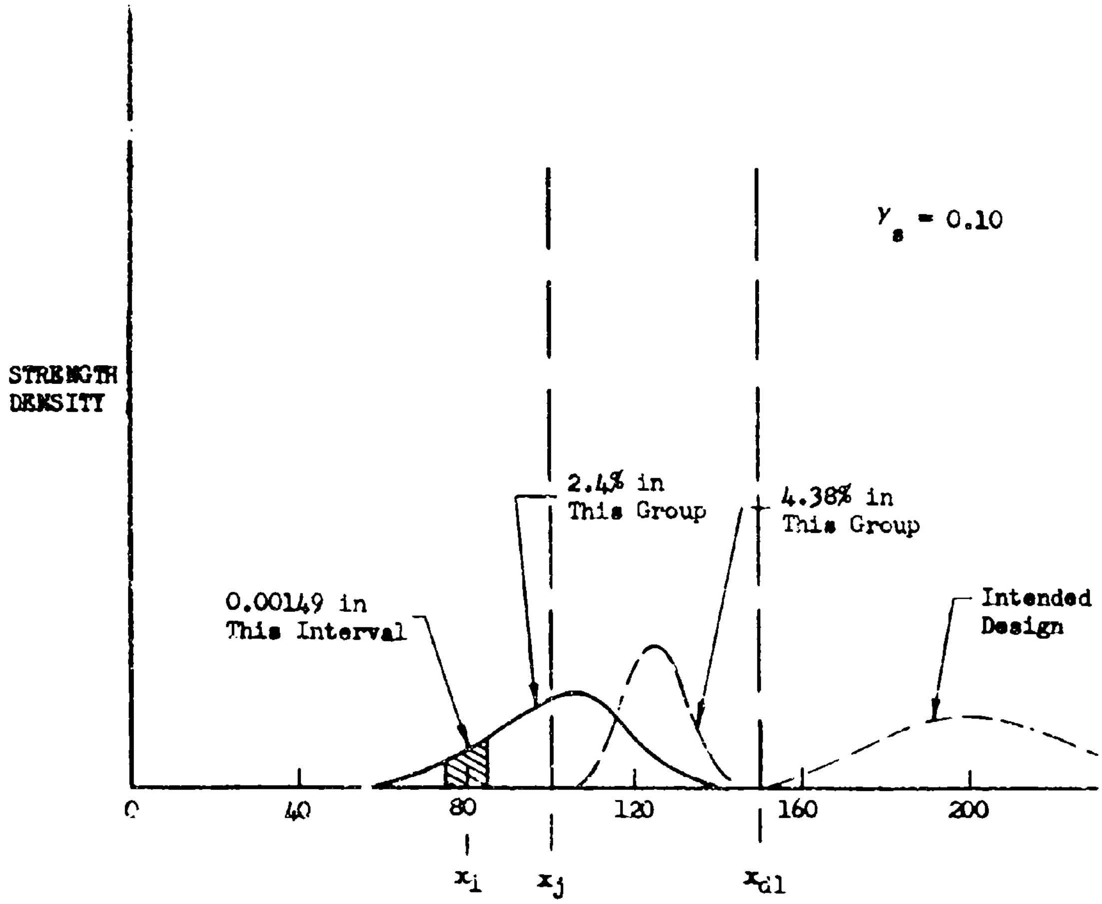


FIGURE 8. FAILURE DISTRIBUTION COMPOSITION

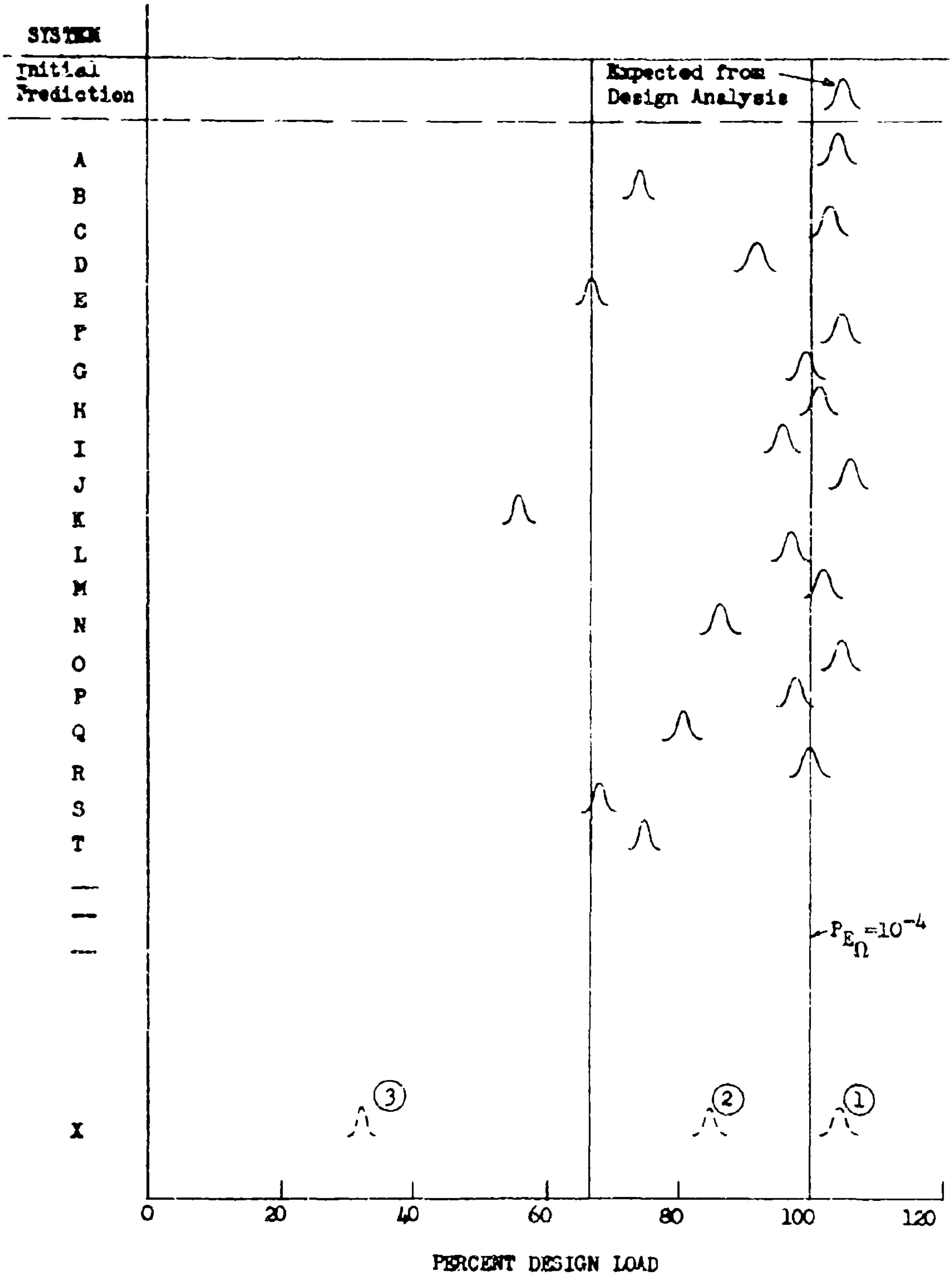


FIGURE 9. STRENGTH DISTRIBUTION IN A COMPLEX OF SYSTEMS (WITHOUT TEST)

on the top line for the analytical prediction. No specific calculation of this distribution was made in the design of past structures. Nevertheless, if the 99-percent-exceed "allowable" was properly matched to the design load, a distribution such as shown on the top line of Figure 9 would be the result. Because of analytical errors in the various designs, the actual strength distributions before test would be located as shown on Figure 9. The hypothesized distributions are consistent with the data of Reference 6 and Figure 5. Because of errors in the analysis more than half of the vehicles will fail at less than the design load. Some of the strengths will be randomly higher than the mean strength of the particular system and some will be lower.

If a new system designated System X has been designed and analyzed with the expectation of obtaining a distribution corresponding to (1) by procedures comparable to those used on System A to T, the actual distribution might be that of (1), (2), (3) or any intermediate distribution. The true location of the distribution must be considered to be unknown. If no strength test is conducted, it must be assumed that the chances of the mean strength being low are the same as they were in the past as represented by the distribution of the means of Systems A through T. If the System X strength happens to correspond to distribution (1), the system probability of failure will approximate 10^{-4} (Figure 9 assumes that the probability of exceeding the design load is 10^{-4}). However, if the strength happens to correspond to (2), the probability of failure might be 10^{-3}, and if the strength distribution is like (3), the probability of failure might be 0.8.

If all of the various possibilities are considered and integrated by the program of Volume III, the "with error — no test" curves of Figures 6 and 7 are obtained. From this type of information, a decision can be made. Even if the load spectrum is exactly as predicted ($P_{E_\Omega} = 10^{-4}$), the probability of failure in all operations of future Systems X, taken as a group, will be far greater than the tolerable value of 10^{-4} and will approximate 10^{-1}. For this reason, a decision can be made that System X, as it stands, with a complete analysis but no strength test, does not have the desired 0.9999 S.R. It must be understood that in some cases the true distribution of System X is distribution (1). In that case, the S.R. really is about 0.9999. For such systems the decision would be a wrong decision. But there will also be System X's with distributions (2) and (3) where the decision would have been a correct decision.

Taken over a period of time the next 20 systems designed without a strength test must be expected collectively to have the same characteristics as Systems A through T. If so, about one out of ten of the vehicles involved would fail in operation. Obviously, most of the failures would be in systems comparable to E, K and S. Very few if any would be in Systems A, C, F, G, H, etc. But, until the failures began to occur, no one would known which systems were the E, K and S's. The designers of System X might be very confident that "their" system was error-free. But it must be remembered that the designers of Systems A through T were equally confident. More than half of them were wrong in their confidence. It would be presumptuous for the future designers of System X to assume that they alone could design a million or even a thousand structures without ever faltering and producing a System E, K, or S.

In terms of the functional diagram of Figure 1, the best information available as part of the Actual State Information System says that a decision should be made that the actual S.R. of a newly designed structural system, before strength test, must be approximately 0.9. The S.R. may be higher but such a decision cannot be made on the basis of past experience. To decide otherwise should require a preponderance of evidence to show why the past experience will be improved upon. In other words, the burden of the proof should be on anyone who chooses to assume that the future record will be better than the past.

The improvement in analytical accuracy would have to be substantial before much improvement in S.R. would result. Figure 5 shows that about one in one-hundred test structures fail at one-third the design load. If this were improved tenfold to one in a thousand, the S.R. would improve less than an order of magnitude as shown on Figures 6 and 7. Furthermore, the consequences of deciding to accept a system like E, K, or S are so drastic that the "accept" decision should be made only on the soundest possible basis.

Since it can be decided that a new structural system does not have a provable, before-test structural reliability greater than about 0.9, such structures could not be considered to have met any of the desired levels of S.R. listed on Table I. If this be so, on what basis can a decision be made that the S.R. is sufficiently high? The next shows that testing will provide some answers to the problem.

d. Error Disclosure by Testing

(1) Error Disclosure Principles

The previous section showed that the structural reliability of systems that have not been strength tested is inevitably much lower than desired because of the possibility of analytical error. If a large number of tests of the structural system could be conducted, the strength distribution could be determined accurately and the possibility that there was an error in the analysis would not need to be considered. However, Volume I, quoting Taylor and Lusser, notes that a rule of thumb for the number of specimens required to estimate the chance of failure is ten times the reciprocal of the chance. This means that if the relatively modest reliability of 0.9999 were the goal, one-hundred thousand specimens would have to be tested. Grose[7] has pointedly observed that funding of test programs to prove reliability numbers like this would bankrupt the nation. It is obviously not feasible to determine the structural reliability of a vehicle by experimental means.

A different approach is necessary. The philosophy was developed in Reference 8 that the function of testing is to act as an error "discloser," not a reliability "prover." If a single test article fails to pass a specific strength test, it can be considered that this test failure has disclosed an error. This action still does not prove what the reliability actually is, either before or after the test. The rejection of understrength designs by means of the test is not absolute. The strength of individual articles of any particular design has a distribution about the mean strength, wherever that mean is. A test article from a system whose mean strength is much lower

than the test load may survive the test. This would occur if the test article randomly happened to be much higher in strength than the mean. Such a possibility must be considered in determining the structural reliability of a design after one or more test articles have passed a designated test.

The main concern is whether a system that is significantly understrength will pass the strength test. Reference 9 presents a discussion showing that a system whose mean is at 100 and whose strength scatter is 0.05, similar to the example on Figure 8 of this report, will have a probability of surviving a test to 150 of only 10^{-24}. In such case, the probability previously computed to be 0.00146 becomes 0.00146×10^{-24}, or approximately 10^{-27}. This means that the possibility of failure at 80 has been reduced to a negligible value for a system whose design strength was intended to be 150 but which happened to have its mean at 100 and which had successfully passed a strength test to 150. It cannot be emphasised too strongly that this high degree of certainty in the rejection of all grossly understrength systems is the key to the new procedure described in this report.

In the previous discussion it was pointed out that the reliability goal would be attained if the frequency of exceeding the omega condition was equal to the complement of the desired S.R. and if the allowable corresponded to the omega load. But then it was pointed out that the frequency of making analytical errors results in the error function dominating the structural reliability determination. Then, the strength test is described as an error discloser reducing the probability that an understrength structural system will be accepted for operations. The criteria problem is to provide a procedure to decide, after a test is conducted, whether or not to accept for operations a newly-designed structural system.

The probability that a particular system will have a low mean strength but still pass a test to a significantly higher load is drastically reduced from the probability of being at that level if no test is conducted. For instance, a system such as "Q" on Figure 9 has a probability of 1:31500 that it will pass a test to the design load. Earlier, it was noted that systems like E and S have only one chance in 10^{24} of passing the tests. Therefore, almost all the low strength systems on Figure 9 will fail prematurely during the test, disclosing their weakness. It is almost immaterial that System E may fail slightly on the high side of its mean strength and System S slightly on the low side. Both are so low that the situation can only be the result of a gross miscalculation of the design strength. In most cases, the cause of the problem is evident immediately after the failure.

It is assumed that, in each case, the design is corrected as necessary after a test failure and then retested until the required test load is sustained. This has the effect of eliminating the deficient design and replacing it with a stronger design. The effect of this on the systems pictured on Figure 9 is shown on Figure 10. Several pertinent and interesting situations are depicted on Figure 10. System C is a system with no error in the analysis, yet it happened to fail slightly below the required test load. This will happen occasionally where there is a scatter in the distribution of failing strength. It cannot be helped. The redesign, as shown on Figure 10, is minimal. Such redesigns of a truly acceptable system will be rare. In

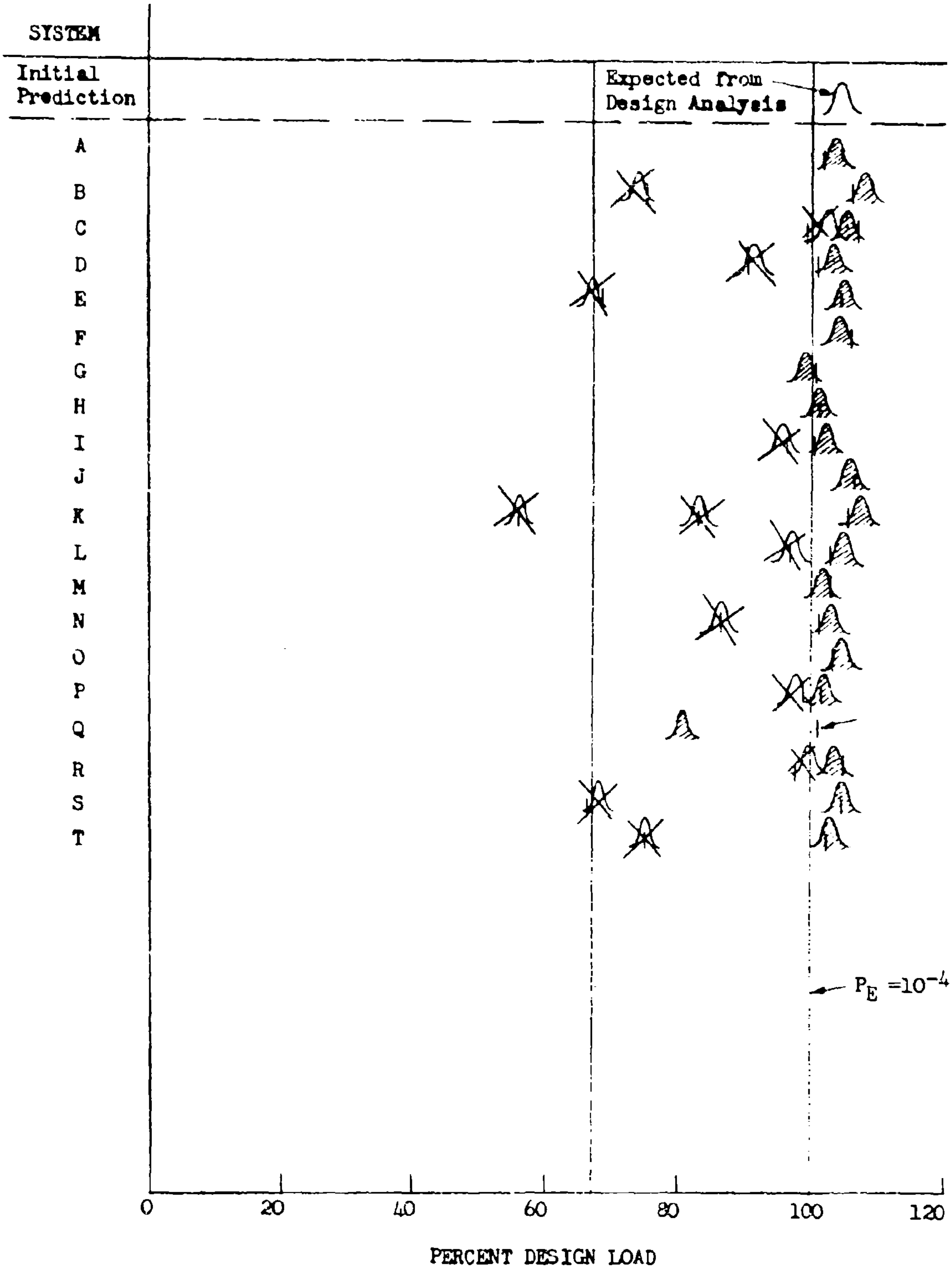


FIGURE 10. STRENGTH DISTRIBUTION IN A COMPLEX OF SYSTEMS (AFTER TEST)

effect, they become part of the cost of obtaining truly reliable structural systems. As far as S.R. is concerned, the redesigned System C is more reliable than necessary so it is obviously acceptable.

System G is slightly understrength but passed the test successfully. It will become operational. It is doubtful that the understrength will ever be apparent because most of the System G structures would have to be loaded to about 145 to 150 percent of the limit load before they failed. This, of course, still represents a gross overload. In any accident investigation, it would almost certainly be concluded that System G was overloaded, not that it was understrength.

System K shows a system failing well below limit load, being strengthened, and failing a second time. After the second strengthening, the system passes the test. Reference 6 records many instances of repeated failures on the same structure. The point to remember is that, after a reasonable number of tests and strengthening, the structure can finally be considered reliable. This is not the same thing as repeatedly testing the same design until finally the random structure that is any arbitrary amount over the mean strength is found and it alone of all the structures tested is successful. Neither is it the same thing as testing 5 or 10 nominally identical structures and requiring that they all survive the test the first time.

System Q is shown with a strength that happens to be substantially below the design strength but which qualified for operation because of an extremely rare, random high strength for the test article relative to the mean strength. Even this much deviation from the desired strength will only increase the failure rate from one-in-ten-thousand to one-in-a-thousand. This System Q illustrates the point that one test cannot guarantee that each and every design will achieve the desired S.R. What is accomplished is that the incidence of System Q's that are accepted inadvertently will be very small compared to the overall failure rate that is considered to be tolerable. If all the Systems A through T depicted on Figure 10 are considered collectively as one complex of systems, the total probability of a new system failing during operation can be calculated considering the probability of analytical error and the probability of disclosing the error during a strength test.

(2) Test to Omega (Ultimate) Loads

A series of curves such as those on Figure 11 can be calculated, using the program described in Volume III, to show the structural reliability that will be attained with consideration of the probability of analytical errors according to equation (3) and the probability of disclosing the error by one test to omega (ultimate) load. The data on Figure 11 is based on the assumption that the loading spectrum is defined by two points. The probability of exceeding the omega load is equal to the complement of the desired S.R. and the probability of exceeding limit is as shown on Table I.

As long as the probability of exceeding the omega load corresponds to the value listed on Table I, the corresponding S.R. will be attained over a wide range of other pertinent variables. If operational factors of safety considerably higher or lower than 1.5 are associated with the loads while the probability

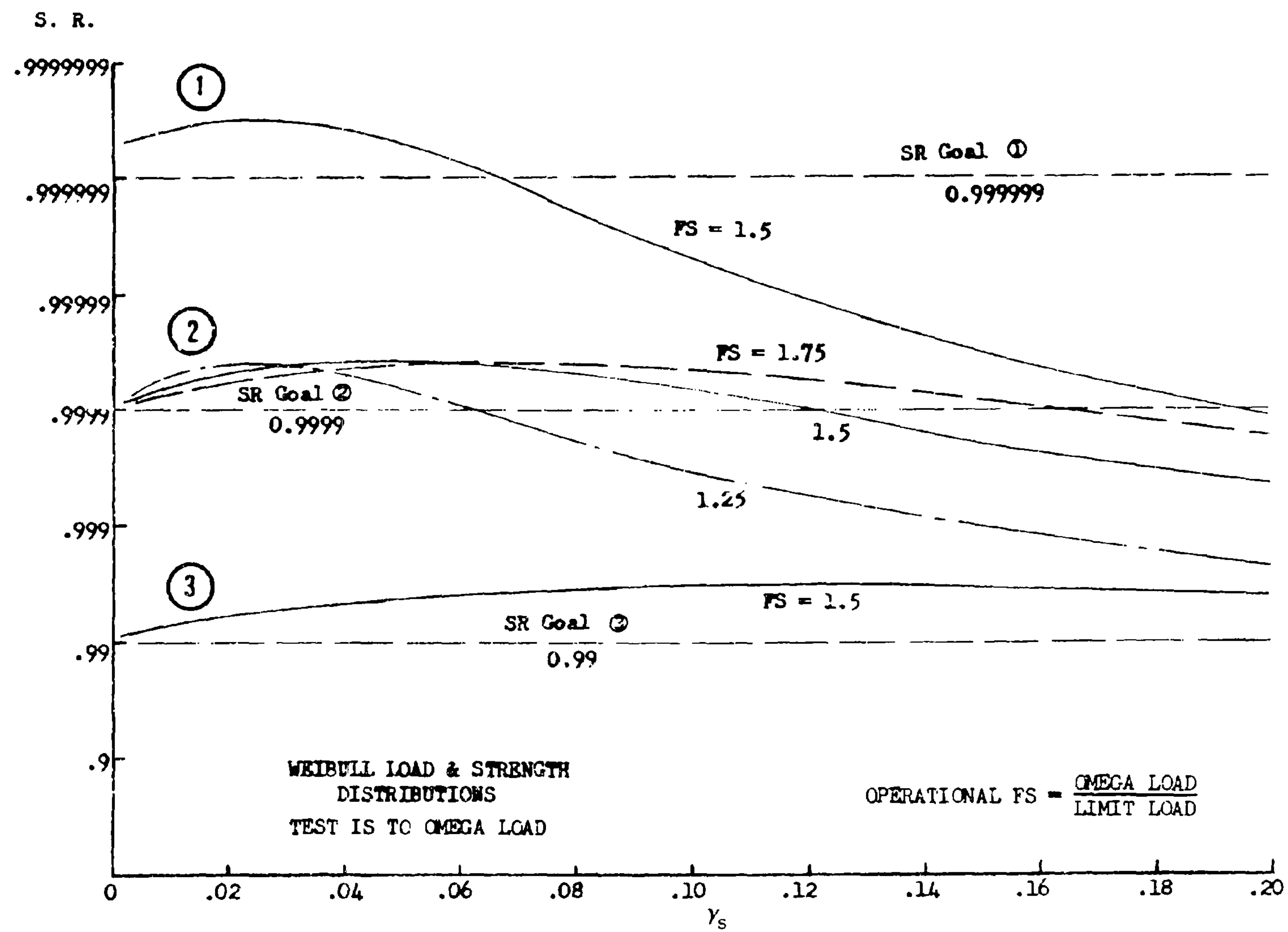


FIGURE 11. STRUCTURAL RELIABILITY - STANDARD ERROR FUNCTION - ONE TEST

of exceeding limit remains at the suggested value from Table I, the resulting load spectra would be as shown on Figure 4. The level of S.R. attained does not vary significantly. This phenomenon is shown for the middle S.R. group on Figure 11. An alternative interpretation on Figure 4, that would not affect the results of Figure 11, is to consider that the load at 67 percent of omega is the limit load for all three spectra. Then, these spectra become three versions of spectra where the F.S. equals 1.5 but the probability of exceeding limit load varies from 0.07 to 0.0038. Either way, the conclusion to be drawn is that the probability of exceeding omega load is the major factor determining the level of S.R. achieved after testing to that omega load.

Examination of Figure 11 discloses that the desired S.R. is equaled or exceeded at the low and moderate values of γ_s, but is not attained at the larger values of γ_s. This reduction in S.R. at the large values of γ_s is due to the greater probability of a system passing the test with a randomly high-strength article and then failing in operations with a randomly low-strength vehicle. If a system such as System Q on Figure 10 with its mean strength midway between limit and ultimate load is considered, the difference between a low-scatter and a high-scatter system can be clarified. Suppose that System Q is presented for static test. It was previously noted that there is a 1:31500 chance of passing the test. The chance of this system failing at limit load is also 1:31500 (Gaussian distribution assumed). The probability of passing the test to ultimate load and subsequently failing at limit load is $\frac{1}{31500} \times \frac{1}{31500}$, which is a probability of about 10^{-9}. This probability is predicated on System Q having a $\gamma_s = 0.05$. If γ_s equaled 0.20, the probability of the two events occurring is markedly increased to more than 10^{-2} (seven orders of magnitude greater). With the 0.20 scatter, the chance of passing the test has gone up to about 1:6 and the chance of subsequently failing at limit load is 1:6. The computer program of Volume III integrates the cumulative effects on S.R. of the possibility that the mean strength is at any of the many possible levels instead of the single level used for illustrations here. Nevertheless, this example should serve to spotlight the underlying reason for a decrease in attained S.R. at high γ_s.

(3) Omega Test Factor of Safety

Reference 9 proposed that any desired level of structural reliability could be achieved by a suitable choice of the test load. Although test loads have traditionally coincided with the ultimate design load in the past, there is no inherent reason why this should be so. If the test load is increased beyond the ultimate or omega load, there is a greater probability that the understrength structure will be disclosed and any necessary redesign accomplished. The magnitude of the required increase has been determined by the computer program of Volume III and presented on Figure 12. It is immediately apparent that no extra factor is needed for the region of relatively low γ_s. Since this is the region where most aerospace structural systems of the past have been located, due largely to the unwritten rules and and general state-of-the-art considerations, the past practice of testing only

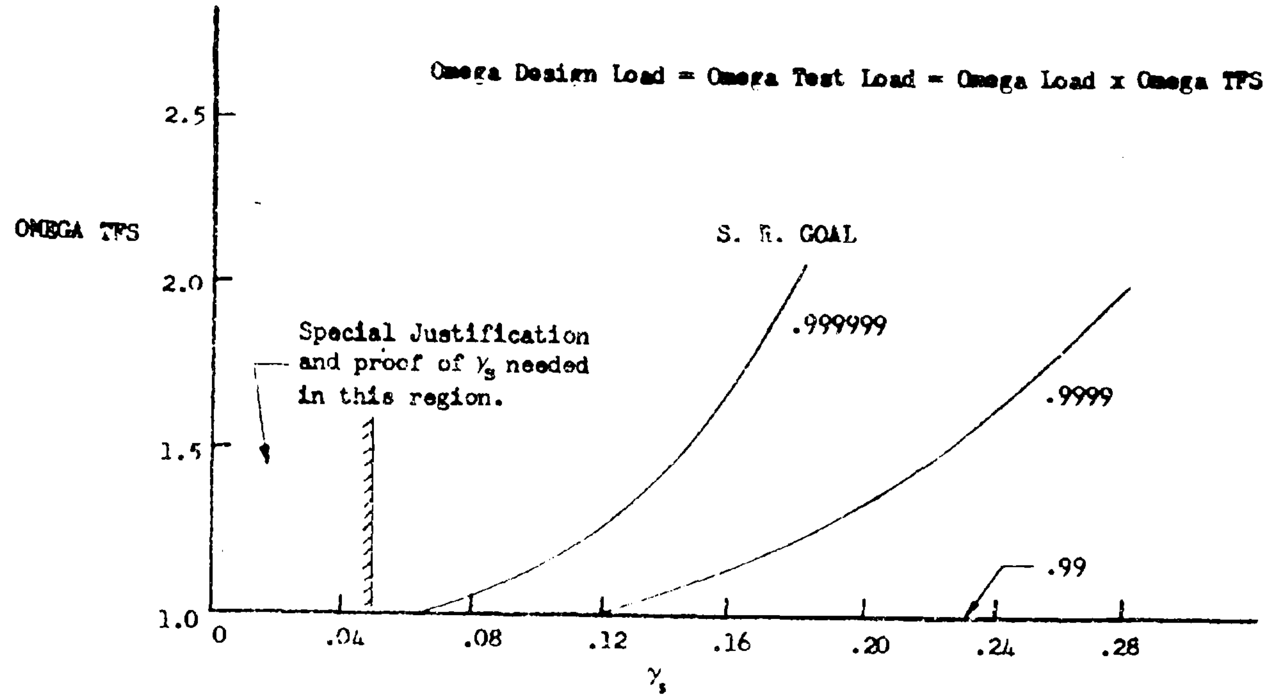


FIGURE 12. OMEGA DESIGN AND TEST FACTOR OF SAFETY FOR A GIVEN S.R. GOAL VERSUS STRENGTH SCATTER, γ_s

to the ultimate (omega) load is justified by Figure 12. It would have raised serious doubts concerning the validity of Figure 12 if the proposed procedure had called for TFS greater than 1.0 at the lower values of γ_s.

It has generally been accepted that structural materials should be ductile which has minimized the scatter of failing loads due to brittle material structures. Structures that were overly sensitive to dimensional or chemical variation have been avoided. Use of materials beyond the "knee" of the strength/temperature curve has been avoided. By such techniques, a low value of γ_s has been achieved for most structural systems in the past, without an express requirement for a low γ_s. Most of the limitations mentioned above are necessarily being violated in the structures designed for the advanced vehicles of the present and future.

If the omega TFS, as shown on Figure 12, is used to define the test conditions, the S.R.'s for the three levels of loading spectra are all equal to or greater than the desired S.R. as shown on Figure 13. The middle group of curves shows the variation in the predicted S.R. if F.S. larger and smaller than 1.5 are considered and if appropriate omega TFS as shown on Figure 14 is used. Rather than specify a set of omega TFS curves as in Figure 14, it is considered preferable to use a single curve for each level of S.R. desired, as shown on Figure 12. In this case, the S.R. will vary somewhat from the desired value of 0.9999, but will be a good approximation of the value as shown on Figure 15.

Having shown that the S.R. resulting from use of the curves of Figure 12 are not affected significantly by major variations in the F.S. relationship between limit and omega conditions, the effect of differences in the assumptions governing other parameters should be examined. The curves on Figures 11 through 15 are computed with the assumption that the distributions involved are Weibull distributions. The program of Volume III can accept normal (Gaussian) and log-normal assumptions as well. The middle curve of Figure 13 has been recomputed using these two assumptions. The resulting S.R.'s are shown on Figure 16. Finally, the sensitivity to different assumptions for the error function of Figure 5 and equation (3) are examined. The computer program has provisions for varying this error function as described in Volume III. The sensitivity is examined by assuming that the analytical accuracy is 10 times better (fewer errors) than documented by Reference 6 or 10 times worse (more errors). The results of this analysis are shown on Figure 17.

It is obvious that the coefficient of strength scatter, γ_s, is a very important parameter in the new procedure. Since it has not been explicitly considered in the SDC of the past, the available data on γ_s is limited. This problem will be discussed further in Section VII. However, the S.R. resulting from design by analysis and test is not overly sensitive to errors in the determination of γ_s. Figure 18 shows the S.R. that will result if γ_s is actually twice the value predicted. It is very unlikely that a miscalculation of this magnitude will be made once some experience in predicting γ_s is attained.

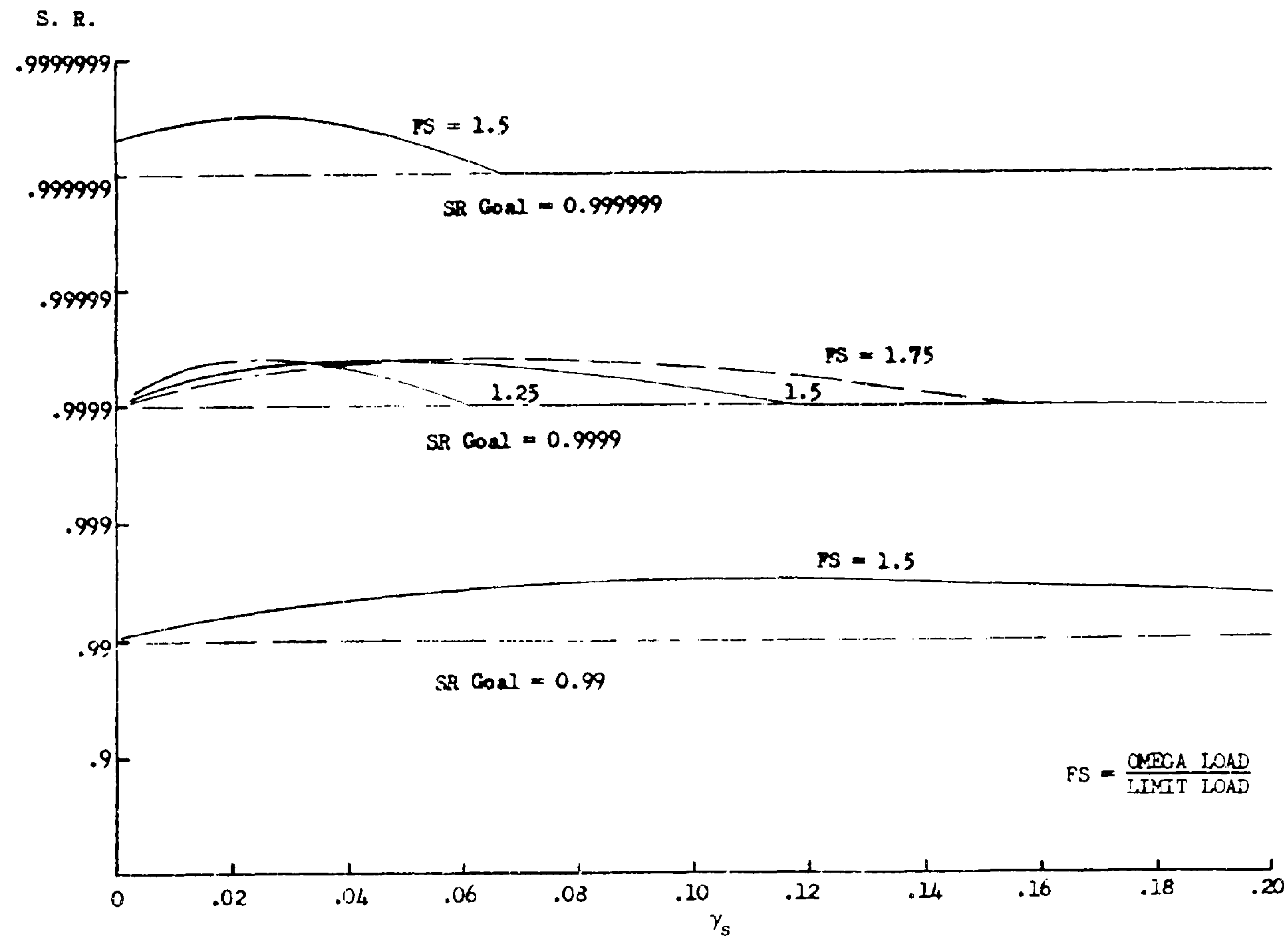


FIGURE 13. STRUCTURAL RELIABILITY USING OMEGA TEST FACTOR OF SAFETY

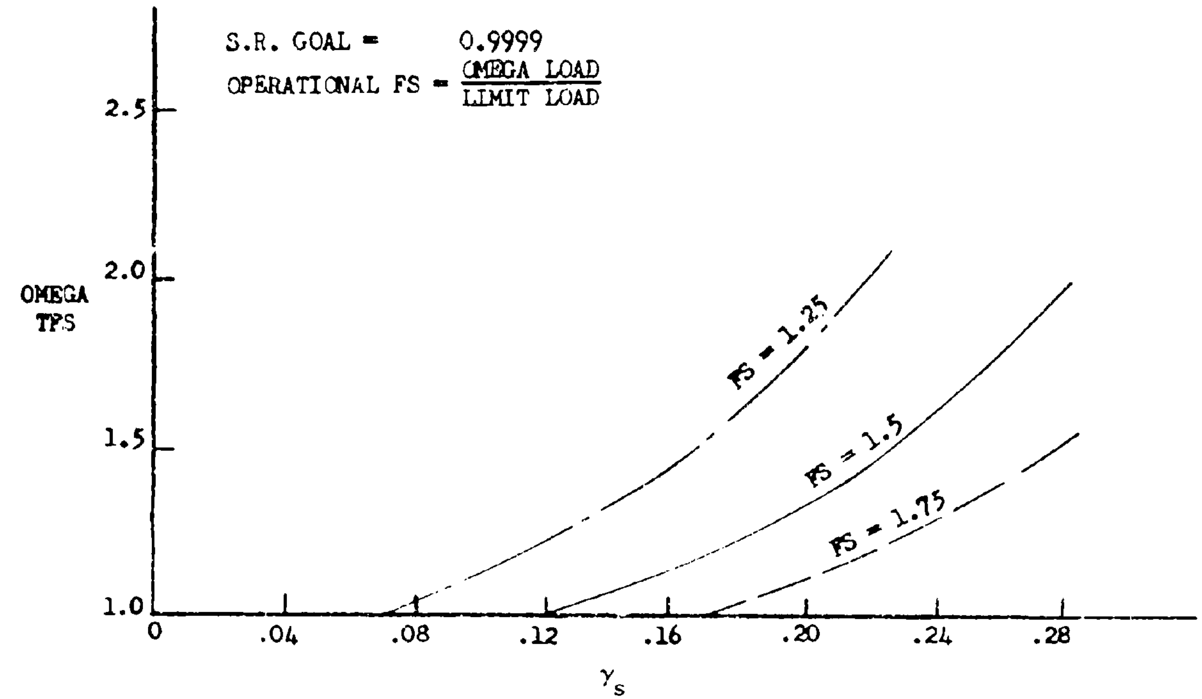


FIGURE 14. OMEGA TEST FACTOR OF SAFETY FOR SEVERAL OPERATIONAL FS

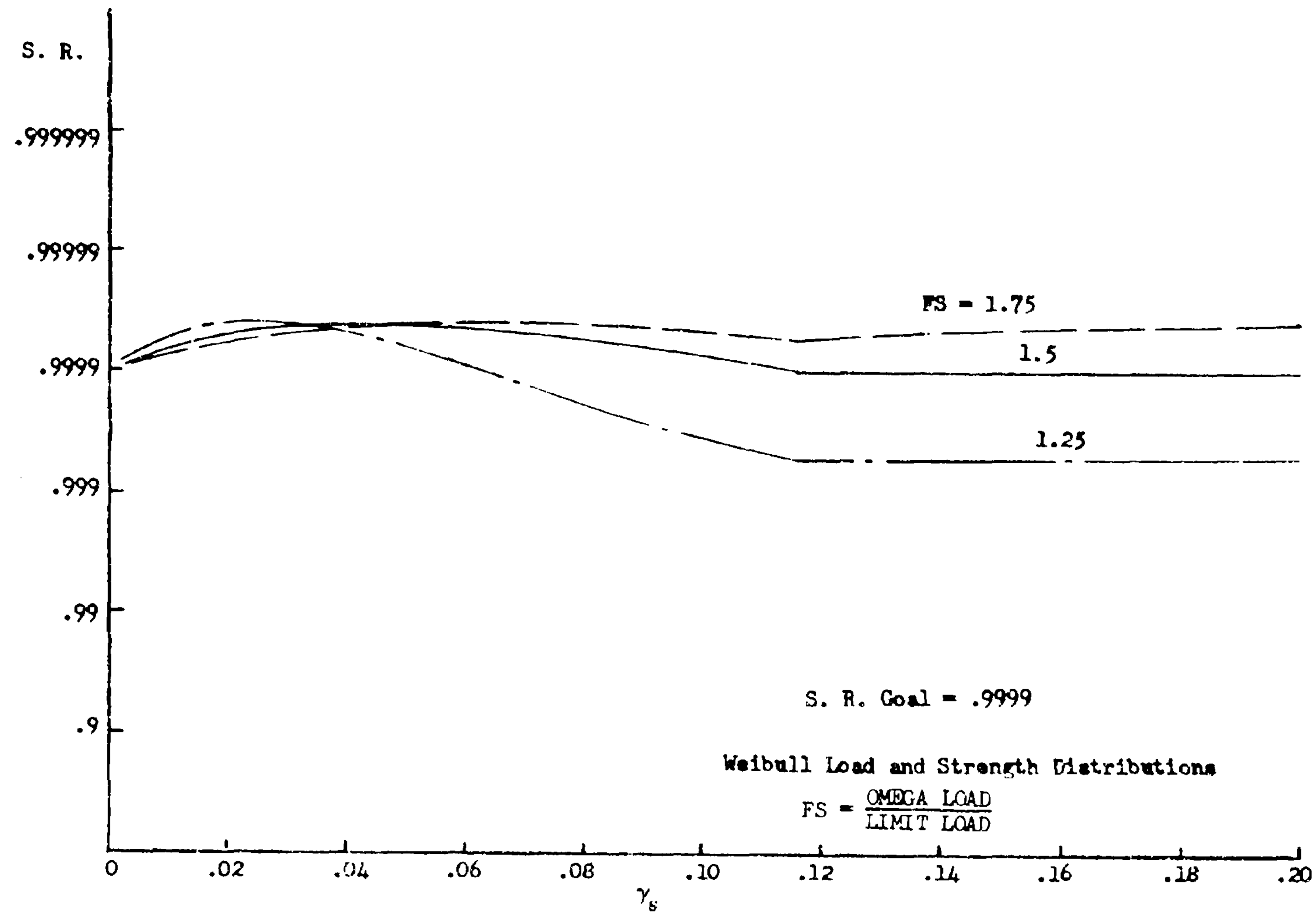


FIGURE 15. STRUCTURAL RELIABILITY USING OMEGA DESIGN AND TEST FACTOR OF SAFETY DESIGNATED FOR FS = 1.5

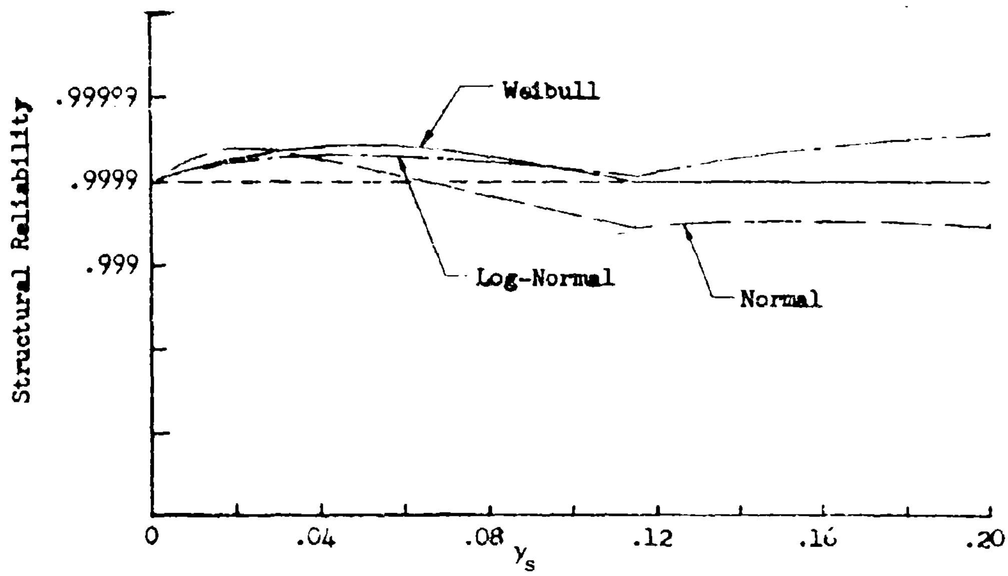


FIGURE 16. EFFECT OF DISTRIBUTION FUNCTION

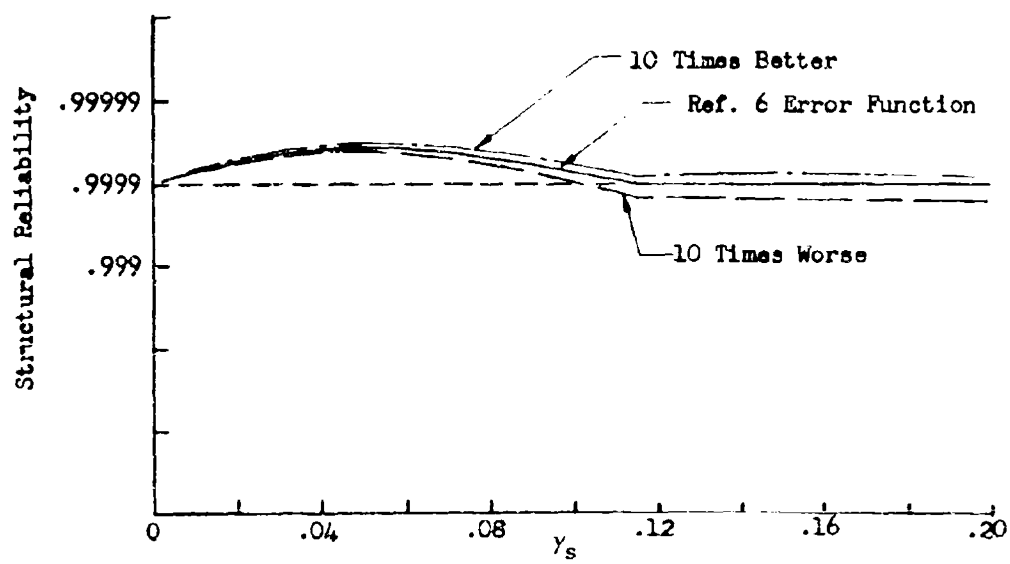


FIGURE 17. EFFECT OF ANALYTICAL ERROR FUNCTION

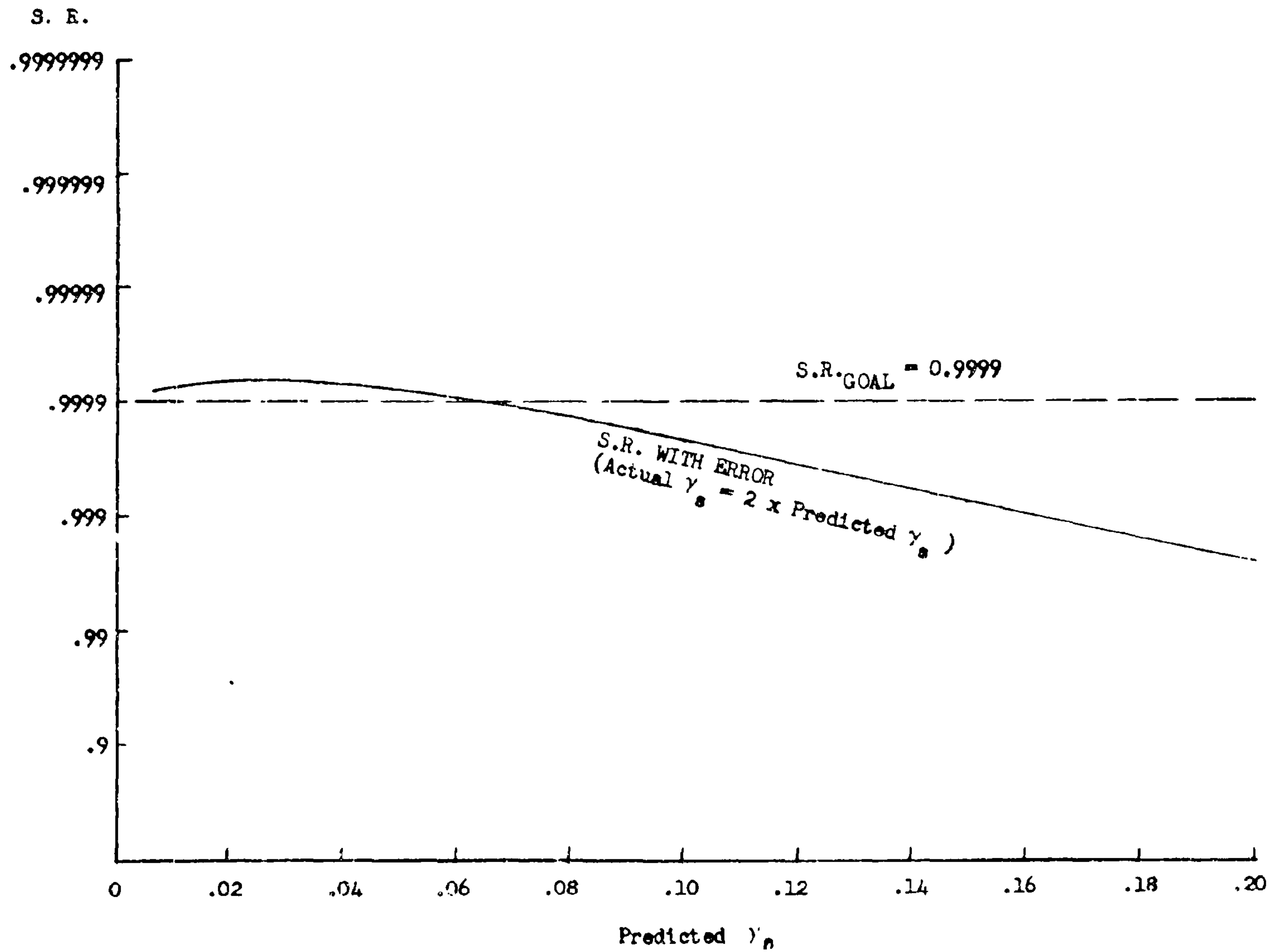


FIGURE 18. EFFECT OF ERROR IN PREDICTED SCATTER

If the results from all of these varied assumptions are combined as on Figure 19, it appears that a good approximation of the desired S.R. is obtained so long as three conditions are met. These are: (1) the frequency of exceeding the omega condition corresponds to the complement of the desired structural reliability, (2) the design allowables are matched analytically (zero M.S.) to design loads obtained by multiplying the loads at omega conditions by the omega TFS shown on Figure 12, and (3) a representative test article sustains the loads corresponding to the design conditions. From this theoretical analysis of the S.R. that would be attained, a practical administrable procedure for structural design criteria becomes feasible. The goal is established as a particular S.R. number such as one of those in Table I, but the proof of compliance is the physical act of successfully completing a strength test to loads governed by Figure 12.

As discussed in Section 2.3d(1) the purpose of the strength test is to disclose errors in the analysis. In Section 2.3d(2) it was described how System Q had a $\frac{1}{31500} \times \frac{1}{31500}$ chance of passing the test to the design load and then failing at limit load. If a second test were run and both tests were successful, the probability of passing this dual test and then failing at limit load becomes $\left(\frac{1}{31500}\right)^2 \times \frac{1}{31500}$, an extremely unlikely possibility. The decrease in the probability of two consecutive random structures passing the test for the example where Y_s was 0.20 becomes $\left(\frac{1}{6}\right)^2 \times \frac{1}{6}$. This is almost an order of magnitude improvement in the S.R. that results from this second test.

This increment in the S.R. resulting from two or more successful tests to the same load decreases the need to test to as high a test load. The program described in Volume III has the capability to consider such multiple tests. The omega TFS needed for multiple tests is shown on Figure 20. These curves correspond to the middle curve on Figure 12.

This procedure becomes a feasible device for making a positive decision that a design complies with a set of requirements that are statistically based in the face of numerous uncertainties that affect the <u>exact</u> determination of the structural reliability of a particular vehicle. As Figure 19 shows, the results will be close to the desired results. The departure from the precise value of the desired results will never be provable. These small discrepancies will be absorbed in other discrepancies such as the fact that the vehicle ordinarily is not operated throughout its service life precisely as predicted at the beginning of its service. To try to resolve the various unknowns, such as the true shape of the strength distribution curve, to reduce the scatter shown on Figure 19 is essentially impossible. It is feasible to make a parametric study, such as represented by Figure 19, and decide that the variations produced by any reasonable assumption are in the range of acceptable departure from the precise number established as the desired value.

It cannot be emphasized too strongly that the <u>decision</u> that the structural system complies with the requirements which in turn were based on a designated structural reliability goal, does not guarantee that the S.R. will actually be at the desired level. On rare occasions, such as represented by System Q

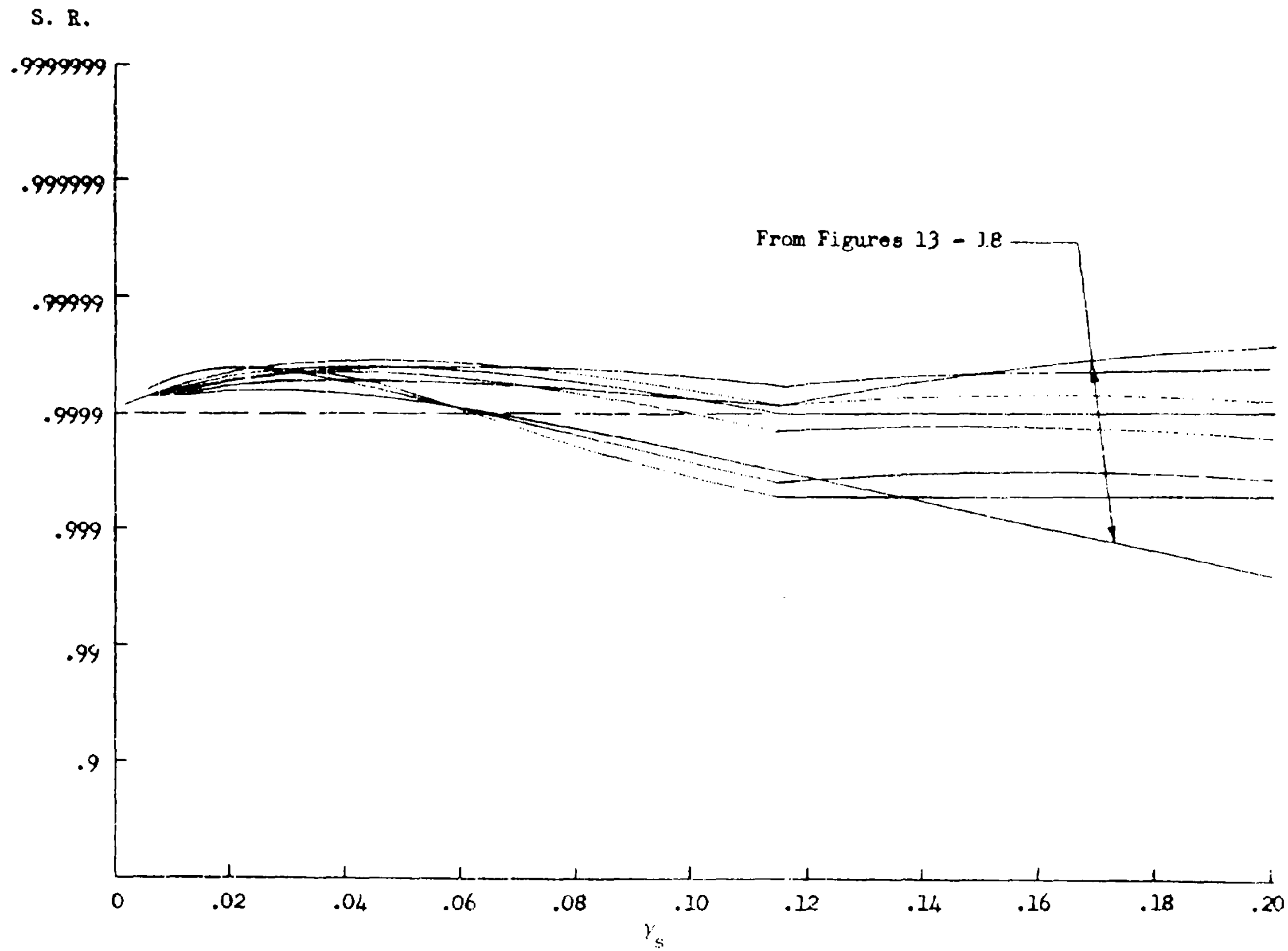


FIGURE 19. COMPOSITE EFFECT OF ERRONEOUS PREDICTIONS

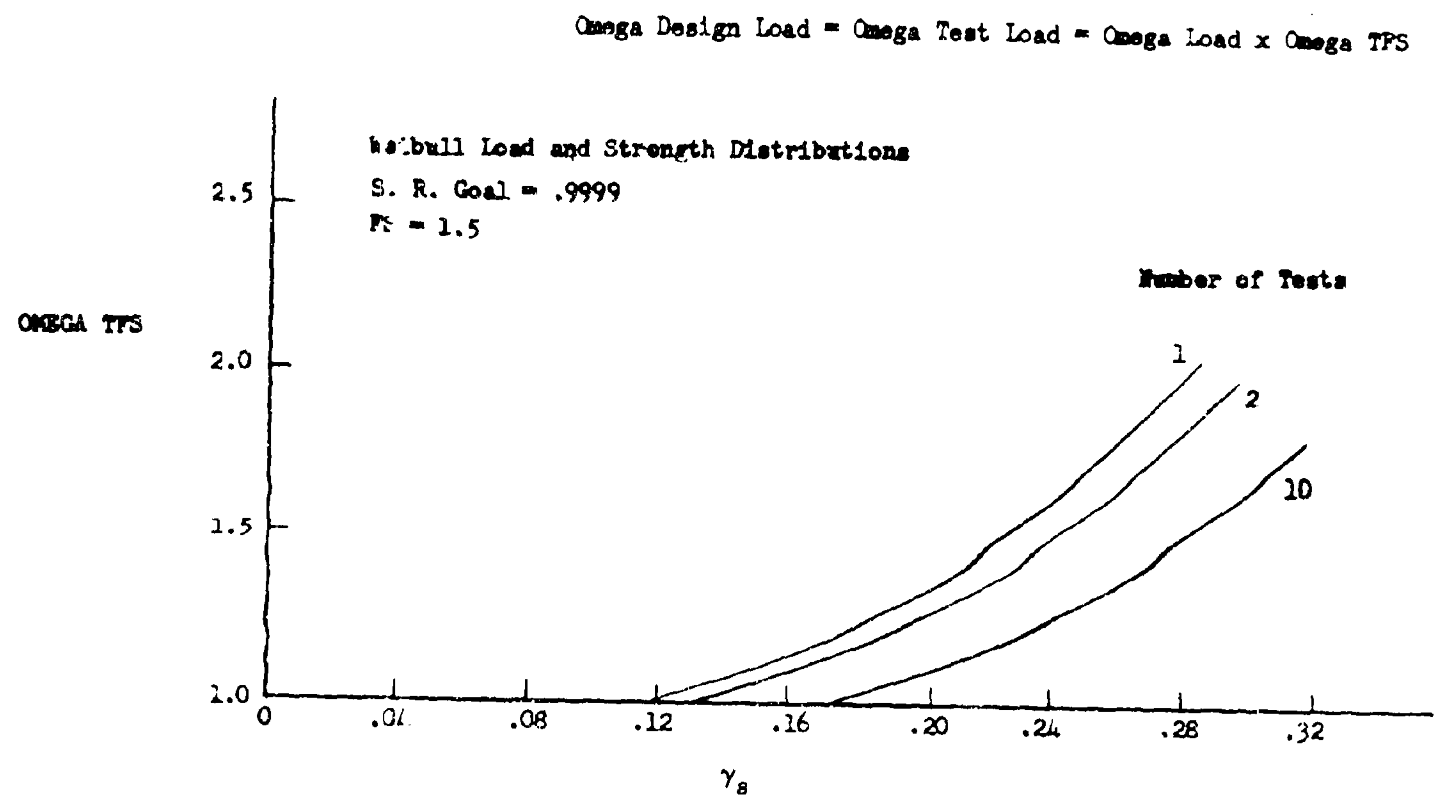


Figure 20. OMEGA DESIGN AND TEST FACTOR OF SAFETY FOR MULTIPLE TESTS

on Figure 10, the structural system will be accepted when it should not have been. Figure 21 shows the results of such a situation. A plot of the failure density distribution for three levels of understrength are shown superimposed on the load distribution. From this, it can be concluded that, at whatever level the mean strength falls, most of the failures occur very close to that level. A derivative of this conclusion is that, if a failure does occur at any level significantly below the omega condition during operational usage, it may be decided automatically without any further analysis that the failure is caused by a deficiency in the structural system. Further, it can be concluded that the probability of failure will correspond approximately to the originally predicted probability of exceeding the condition at which the one failure occurred. If operations are continued without changing the structural system, additional failures can be expected every time the operational conditions approximate the level where the first failure occurred. This capability to decide is vital to the administrative practicality of the proposed procedure. This capability overcomes one of the problem areas for the Purely Statistical Structural Reliability System as described in the evaluation of that system in Section 3.4 of Volume I. It was noted in that evaluation that statistical data on structural failures and successes during operational usage of the vehicle are inevitably insufficient to make decisions as to the cause of an operational failure and the corrective action to be taken.

(4) Limit Test Factor of Safety

The procedure developed to this point has shown how it is possible to make decisions on a deterministic basis that a structural system has attained a designated structural reliability. If this were the only definition of the Desired State of the structure, the procedure would be complete. However, there are other considerations that should be introduced. These will modify the procedure somewhat but will not change the basic approach. The first of these is to bring the Limit Condition into the picture. In the development of a rudimentary system in Section 2.3a, the concept was introduced of the Limit Condition representing the upper limit or boundary of operational conditions that could be called normal or expected. Since Limit Conditions are normal, they are permitted conditions. The earlier discussions suggested that a desirable goal would be no failures at Limit Condition or less. This is not a feasible goal so a finite probability of failure was suggested in Reference 5 and tabulated on Table I. The particular values listed on Table I are based on an arbitrary decision that no more than one percent of the total failures permissible should occur at limit or less. The choice of one percent has a rationale that should justify its use. However, other values could be selected if later developments appear to warrant it.

The basic justification of the one-percent requirement is that failures due to understrength have traditionally been less acceptable in aerospace vehicles than failures due to overload. Therefore, it is not considered reasonable to establish a goal that would accept the occurrence, in the range that must be considered understrength, of more than a small proportion of whatever total number of failures will be tolerated. By definition, operations in this range are permissible. The requirement applied to a high-risk, military vehicle, such as a fighter airplane, can illustrate intuitively the need for

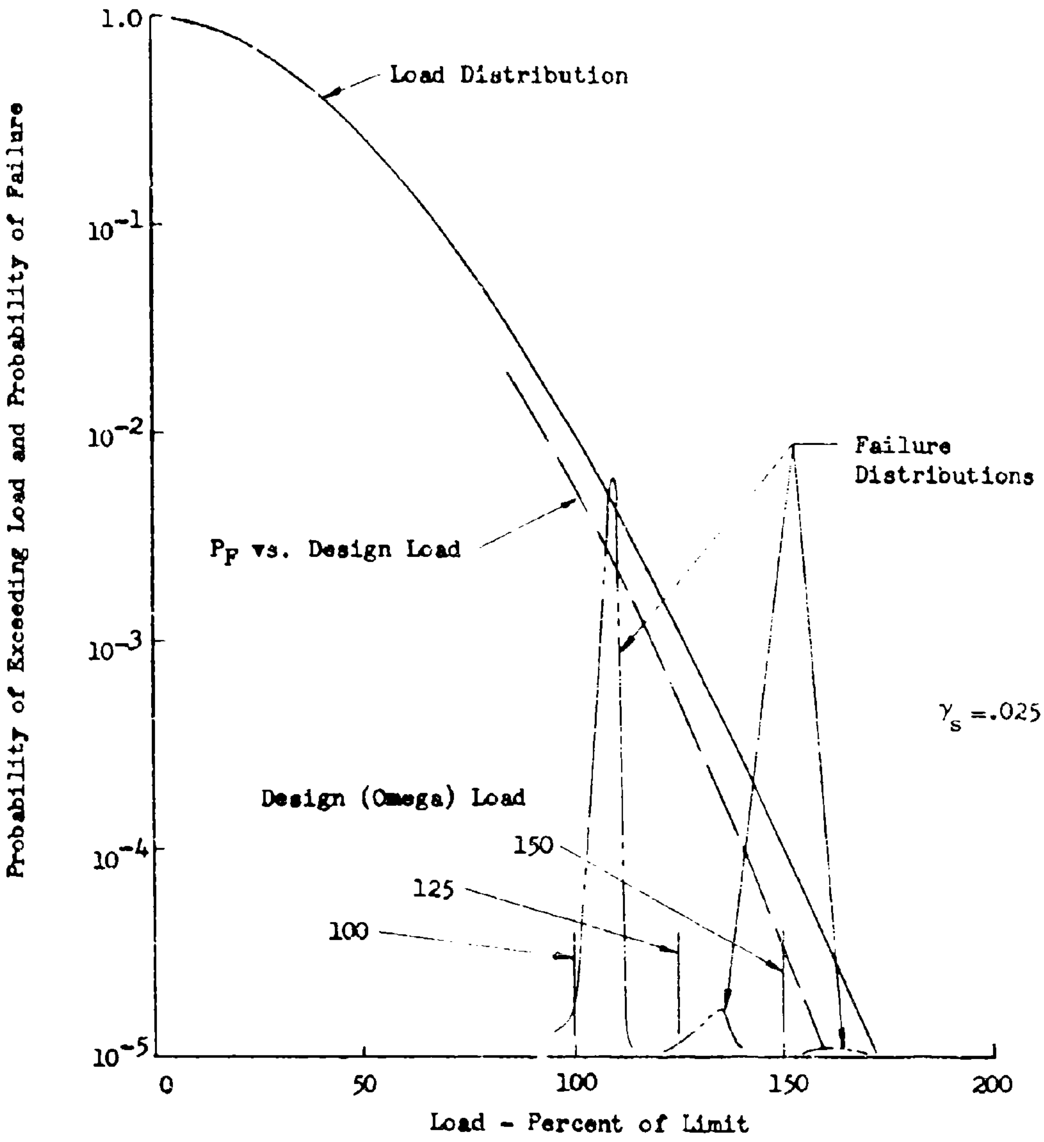


FIGURE 21. FAILURE DISTRIBUTIONS FOR VARIOUS DESIGN LOADS

the one-percent requirement. If the structural reliability goal of 0.99, suggested on Table I were to be adopted, it would mean that approximately 20 out of a fleet of 2000 airplanes would be expected to fail structurally. If the 20 failures all occurred at gross operational overloads approaching 150 percent of the operational limitation, the result would be tolerable. On the other hand, if half of the failures occurred within the operational limitations as defined by V-n diagrams and the other half occurred beyond in the overload range, it is extremely dubious that the 10 failures within the permissible operational range would ever be tolerated. This would be true even though the 20 total failures would be no greater than in the first case. The pilots or users of the vehicle would soon have no confidence in the structural integrity of a vehicle that failed where it was presumably safe and permissible to operate. If the requirement were established that no more than 10 percent of the total tolerable number of failures could occur at limit conditions or less, this would be tantamount to saying that the goal is no more than two failures at less than limit in the fleet of 2000 vehicles. Usually, when a second failure of a given type occurs, it is considered that there is a problem. Also, there are bound to be variations from the goal for various reasons, so there would be some situations where 3 or 4 failures might occur without any particular indication of anything being wrong in the structural design. Therefore, a probability of failure at limit or less of one percent of the total tolerable number of failures seems to be quite a reasonable goal.

If the strength scatter, γ_s, is reasonably low and if the factor of safety is 1.5 as it has been in most aerospace systems of the past, there is no problem. If the total or overall structural reliability is attained, the one-percent requirement is automatically met. It is very likely that this is the reason that the situation has never been recognized as a problem in the past. Figure 22 shows a typical relationship between load spectrum, strength distribution and failure distribution for two typical structural systems. For a narrow-scatter ($\gamma_s = 0.05$) system, essentially all the failures occur near the design load with an infinitesimal portion of the total occurring below limit load. The omega load corresponds to the load at the omega condition which is exceeded in one in ten-thousand vehicles. From Figure 12 the omega TFS is 1.0. Therefore, the design load to which the "allowable" strength is matched analytically and the test load to which a strength test is conducted is identical to the omega load. The strength distribution that would result if there were no error in the analysis is shown by the solid distribution on Figure 22. Section 2.3d(3) considers the distribution of system strength after completion of the strength test to be something like the distribution of Systems A through T on Figure 10. In a group of vehicles such as these most of the failures will occur in those systems whose mean strength is slightly lower than the analytical strength distribution yet which have passed the strength test and been accepted. These would be systems like G, H, I and P. The failure distribution for such a complex of structural systems would be as shown on Figure 22.

When the strength scatter is large, most of the failures will occur far below that design load which will result in the acceptable total failure rate (10^{-4} in this example). Figure 22 shows the comparison of where the failures will occur for the large and small scatter systems. It is apparent that most of the failures in the large scatter system have been shifted to the

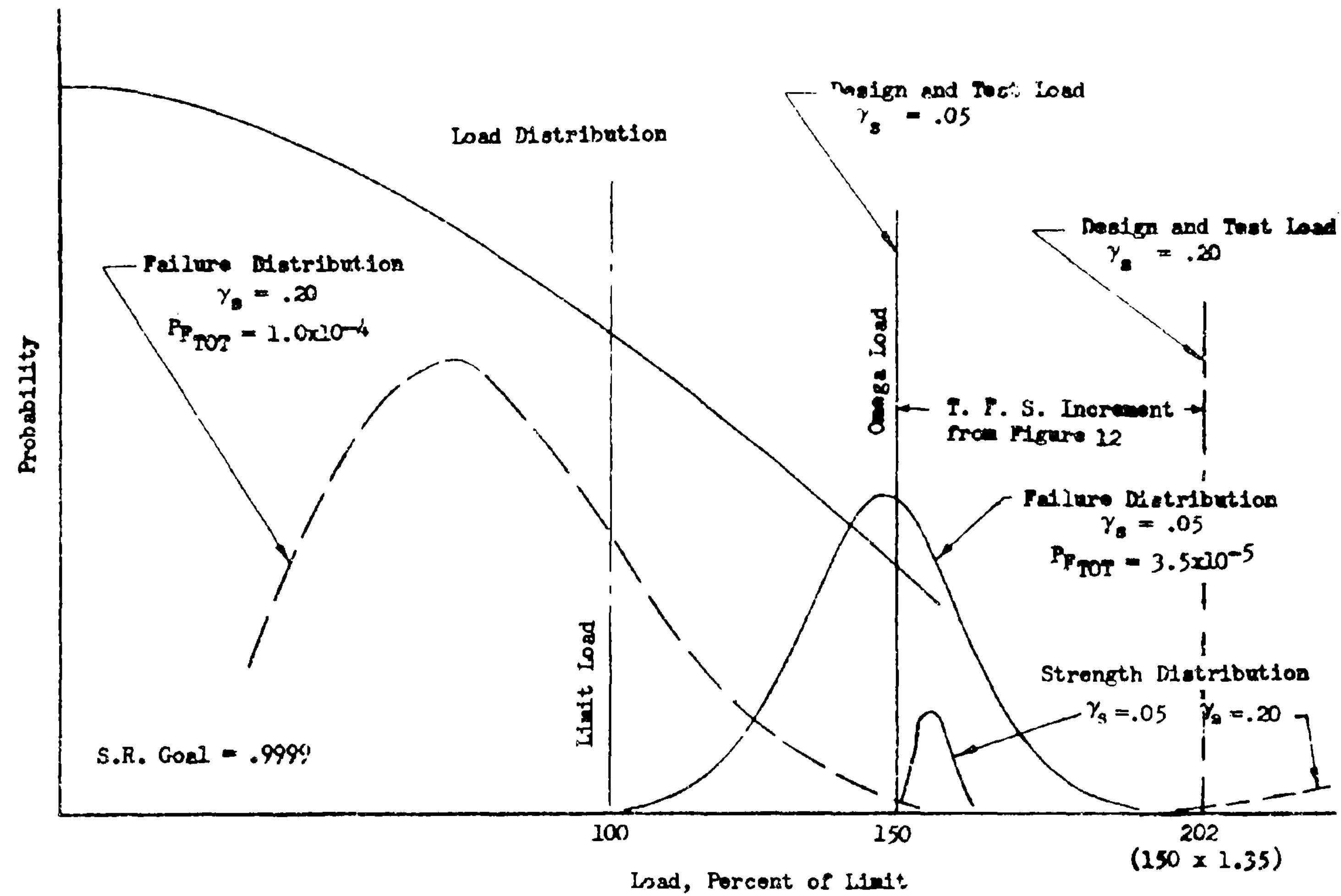


FIGURE 22. EFFECT OF SCATTER ON FAILURE DISTRIBUTION

range below limit condition even though the total number of failures satisfies the SR goal. As just discussed, this does not appear to be a satisfactory situation. A parametric study showing the fraction of the total failures that will occur at limit condition or less for a range of γ_s is shown on Figure 23.

If the "one percent" requirement is adopted, a new design and test requirement can be established. A Test Factor of Safety for limit conditions, separate and distinct from the one established on Figure 12 for omega conditions, can be determined. Its development would be comparable to that discussed in explaining the development of Figure 12. The computer program of Volume III is utilized to calculate the factor that the limit loads associated with each level of structural reliability (as defined on Table I) must be tested to in order to assure that the probability of failure at limit condition or less will be no more than one percent of the total acceptable probability of failure.

$$P_{F_{LIM}} = 0.01\ (1 - S.R.) \tag{6}$$

The necessary factor is shown on Figure 24. The Limit Design Load is equal to the Limit Test Load which equal the Limit Load multiplied by the Limit TFS.

On Figure 24 it is significant that the typical 1.5 F.S. suffices to provide the desired limit S.R. up to a $\gamma_s \approx 0.06$ for the highest S.R. goal and up to $\gamma_s \approx 0.10$ for the lower S.R. goal. The type of structure characterized by a $\gamma_s = 0.06$ would have most (99 percent) of its strength scatter between a range of $\pm$ 14 percent of the mean strength. It is dubious if very many of the aircraft structures that have been fabricated in years past have this large a scatter. Remember that this represents the scatter of nominally identical structures. It does not represent the strength range between an underdesigned structure and the redesigned structure that is produced at a later time.

Since most of the acceptable structural systems of the past undoubtedly fell below these bounds, very few failures occurred below limit condition in properly designed and fabricated structures. When failures did occur at limit or lower, there was almost always some form of gross error in the structure so large that the factor of safety was not expected to provide for it. Thus, no special effort was needed to provide for this type of structural reliability in the past.

In Section 2.3d(3) the increment in S.R. due to multiple strength tests was described. This resulted in a decrease in the Omega TFS as shown on Figure 20. A similar decrease in Limit TFS results if two or more strength tests are conducted. The required Limit TFS is shown on Figure 25.

(5) Conditional Reliability after Testing

The proposed procedure to this point has been directed towards obtaining a structural system with a conditional structural reliability commensurate with the total S.R. desired. This conditional reliability is an intrinsic characteristic of the structure itself. It does not depend on parameters such as the accuracy of the loads analysis or the proper operation of the

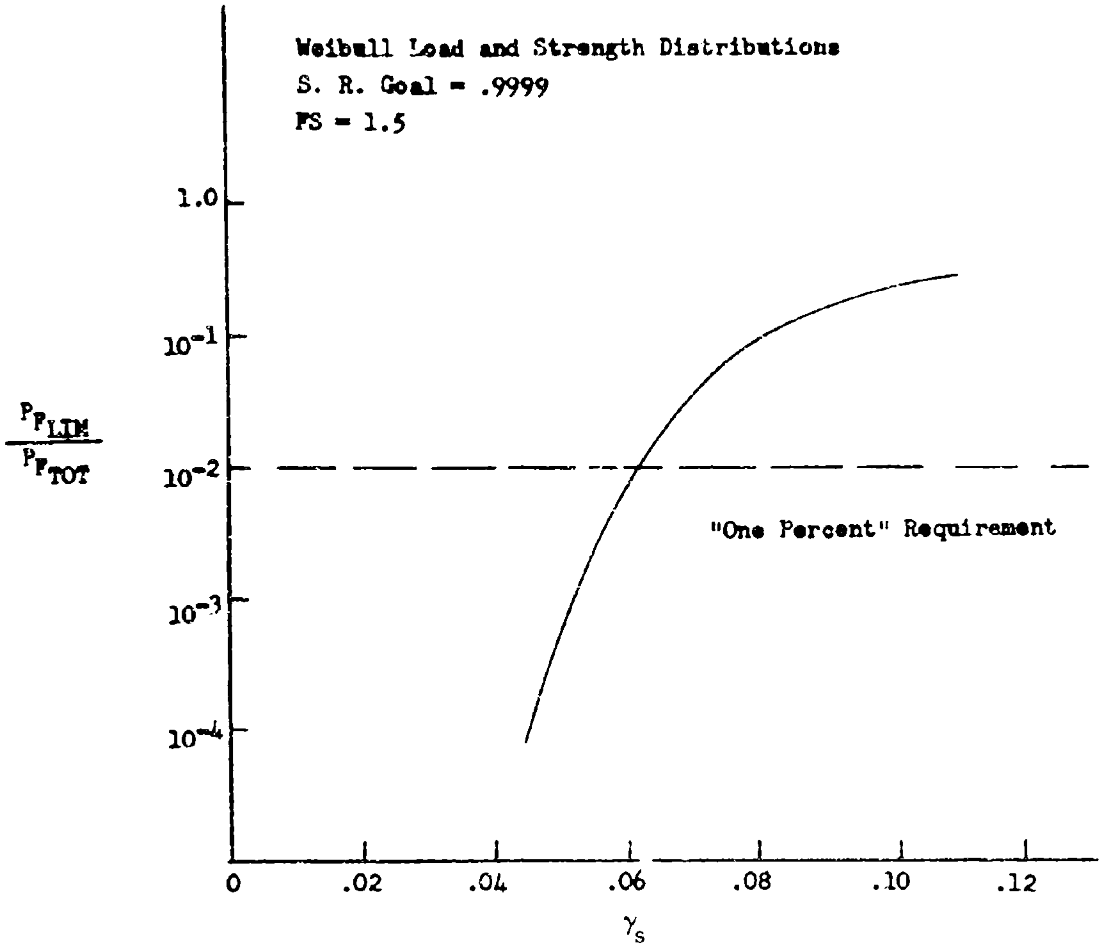


Figure 33. PROBABILITY OF LIMIT FAILURE

Limit Design Load = Limit Test Load = Limit Load x Limit TFS

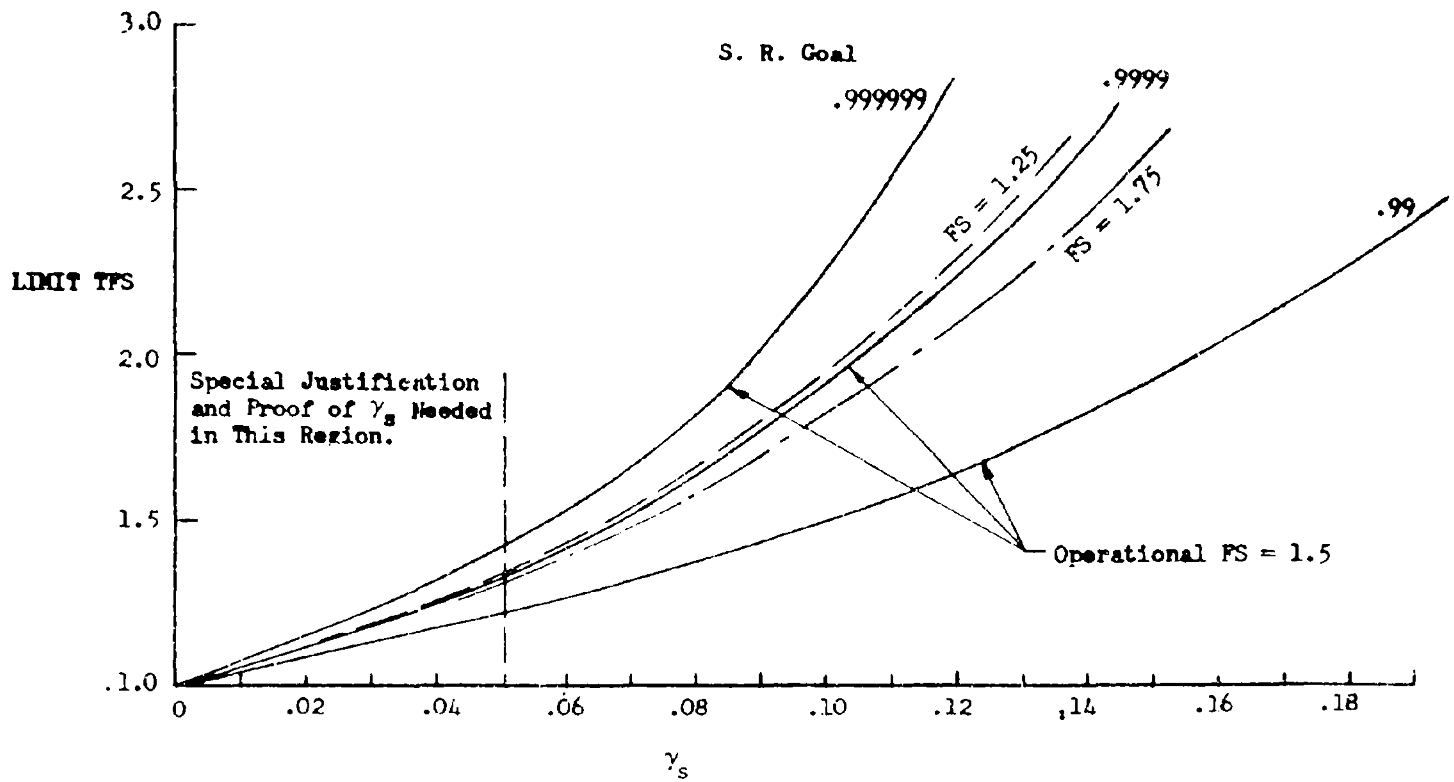


Figure 24. LIMIT DESIGN AND TEST FACTOR OF SAFETY

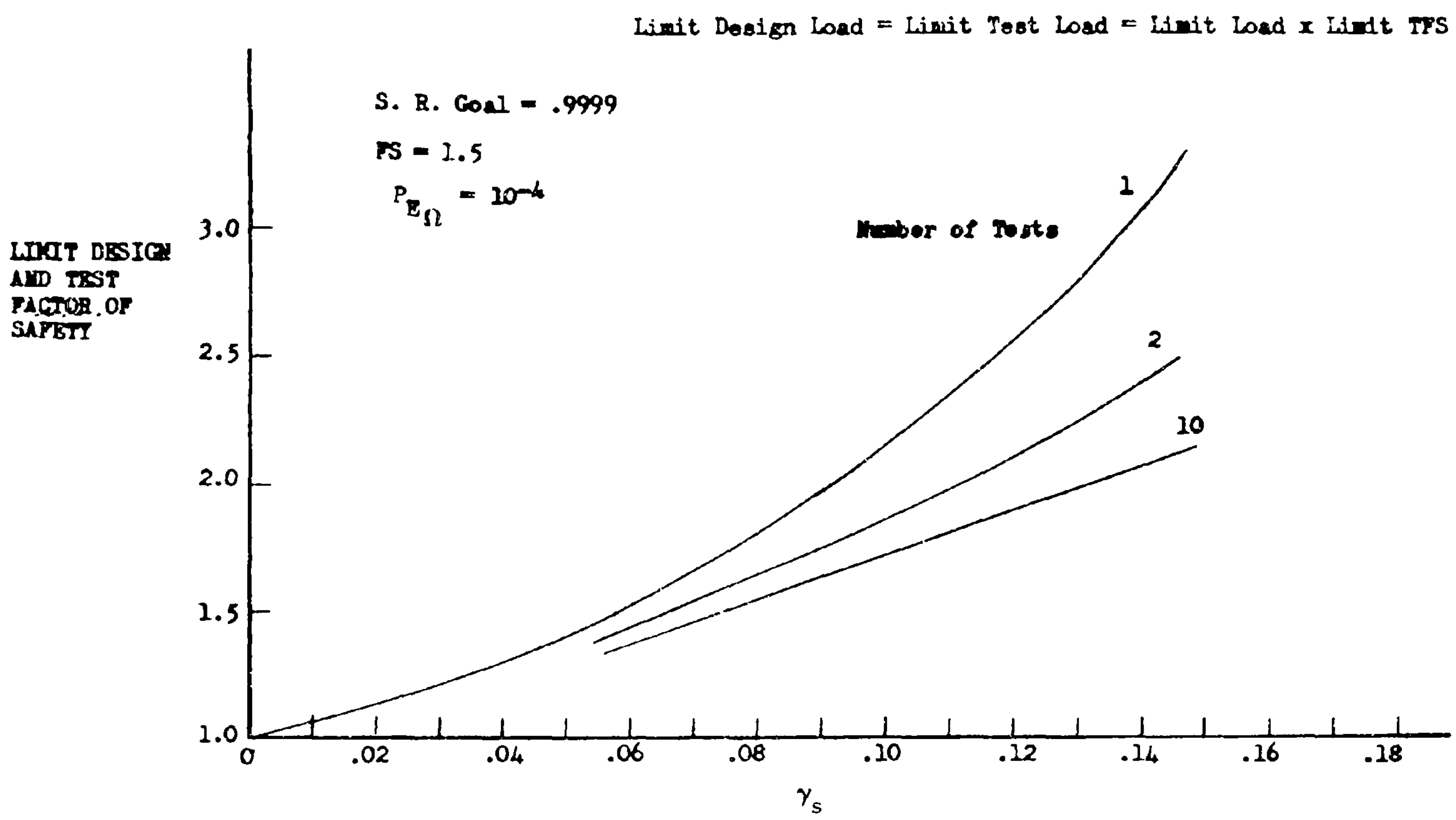


Figure 25. LIMIT DESIGN AND TEST FACTOR OF SAFETY FOR MULTIPLE TESTS

vehicle. There is no question but that the total structural reliability of the vehicle is critically dependent on the correctness of these other parameters. If the choice of limit and omega conditions happened to be very conservative, the total structural reliability would be very high. On the other hand, if the omega condition happened to be exceeded on every vehicle, the total S.R. would approach zero. But the conditional reliability of the structure for the conditions and loads initially defined is immutable. Thus, it can be specified and administered separately from other considerations that affect the total S.R.

These other considerations are not controllable as part of the structural design, per se. Therefore, they should be identified and specified separately from the requirements for the structure itself. This is not to say that the conditions for which the conditional reliability has been established cannot be changed if subsequent developments show the conditions to be inadequate. Such a change in required conditions for the structure may impose a requirement for a change in the structural design. This requires an agreement to change the structure but does not indicate there is anything wrong with the structure for the conditions as postulated initially. In summary, the decision that the structure is acceptable for a prescribed loading can be isolated from the decision that the prescribed loading conditions are acceptable for the particular vehicle system.

e. Loads Error Disclosure by Testing

The previous section discussed how the conditional reliability of the structural system is upgraded by disclosing analytical errors that may occur in the strength analysis. This first conditional reliability is based on the correct determination of the loads associated with the limit and omega conditions and on the correct choice of the limit and omega conditions. Both of these functions are subject to analytical errors comparable to those already described for the strength analysis. The loads ("loads" includes local forces, aeroelastic effects, temperature, acceleration, etc.) error function has not been documented as has the strength error function in Reference 6. Therefore, the computer program of Volume III does not include a loads error function comparable to the strength error function discussed in Section 2.3c. However, it is well known that measured flight loads often differ significantly from the analytically predicted values. For the present a decision can be made concerning the effect of the loads error on the conditional reliability given that the limit and omega conditions are properly chosen and that the structure has been properly designed and tested. It is estimated that the true structural reliability of a system whose loads are based on analysis alone will be reduced from the predicted value to approximately 0.9, comparable to the reduction shown on Figures 6 and 7 for strength errors. It is considered that the accuracy of measuring loads is high enough compared to the accuracy of the statistical parameters so that the conditional reliability for any condition where loads can be measured is not significantly affected by measurement errors. In other words, after a flight loads measurement program, the scatter in the measured value about the true value is negligible. Loads measurements up to the limit conditions would be no different than in the Present System.

Verification of loads beyond limit conditions will pose many obvious problems. Manned vehicles will normally not be cleared for flight beyond the limit condition, which usually represents an operational limitation. Therefore, the verification of the omega loads corresponding to a specific omega condition must be accomplished in whatever manner possible. There are a number of possible procedures that will perform the verification task at least passably well. For example, the simpler (linear) extrapolation of loads measured up to limit condition obviously provides an approximation of loads beyond limit. If there are differences between the original calculations and the extrapolation of the measured values, there must be a valid explanation of the difference or the original calculations must be considered questionable. Often, there are data available from wind-tunnel tests conducted to conditions corresponding to the omega condition. If the wind-tunnel data is validated by the flight-test data up to limit conditions, then it is certainly reasonable to conclude that the wind-tunnel data beyond limit is not wrong. In any event, a decision must be made. As noted on page 5 , the making of decisions is a key element in any structural design procedure. It should be noted that difficulty in making a decision cannot invalidate the need to make the decision. The problem of how much capability beyond limit conditions needs to be provided has always been present, but has been submerged in the procedures of the present system by an implicit decision that whatever operational capability happens to result from the procedure, be it large or small, will be acceptable if it results from the application of the factor of safety to limit loads. It was pointed out in Section 2.2 that a single factor of safety may result in grossly different structural performance capabilities for two different vehicle designs even though both are designed to the same SDC. This is due to the varying amount of operational overload capability that results if the loads are non-linear with respect to the operating conditions. It must be recognised that active consideration of a difficult problem will be more likely to result in a correct decision than if the problem is ignored and the decision made by default. In this case the correct decision will provide the same overload capability for all vehicles in the same operational conditions.

f. Disclosure of Error in Design Conditions

It was pointed out previously that the actual reliability of a structural system is critically dependent on the probability of exceeding the omega condition. The strength may be exactly as desired and the loads for a given omega condition may be very precise, yet the structural reliability may be far less than the desired value if the frequency of exceeding the omega condition is much greater than predicted. Figure 26 shows how the probability of failure varies with the probability of exceeding the omega load. If the structure has its strength exactly as intended with the allowable (the 99-percent-exceed value) exactly at the omega load, probability of failure decreases almost exactly in proportion to the decrease in the probability of exceeding the omega load. Thus, there is an almost one-to-one correlation between the frequency of exceeding the omega condition and the frequency of failure. Figure 26 shows also that, no matter what the loading spectrum, the failures that do occur will occur very close to the omega condition when the strength scatter is relatively low.

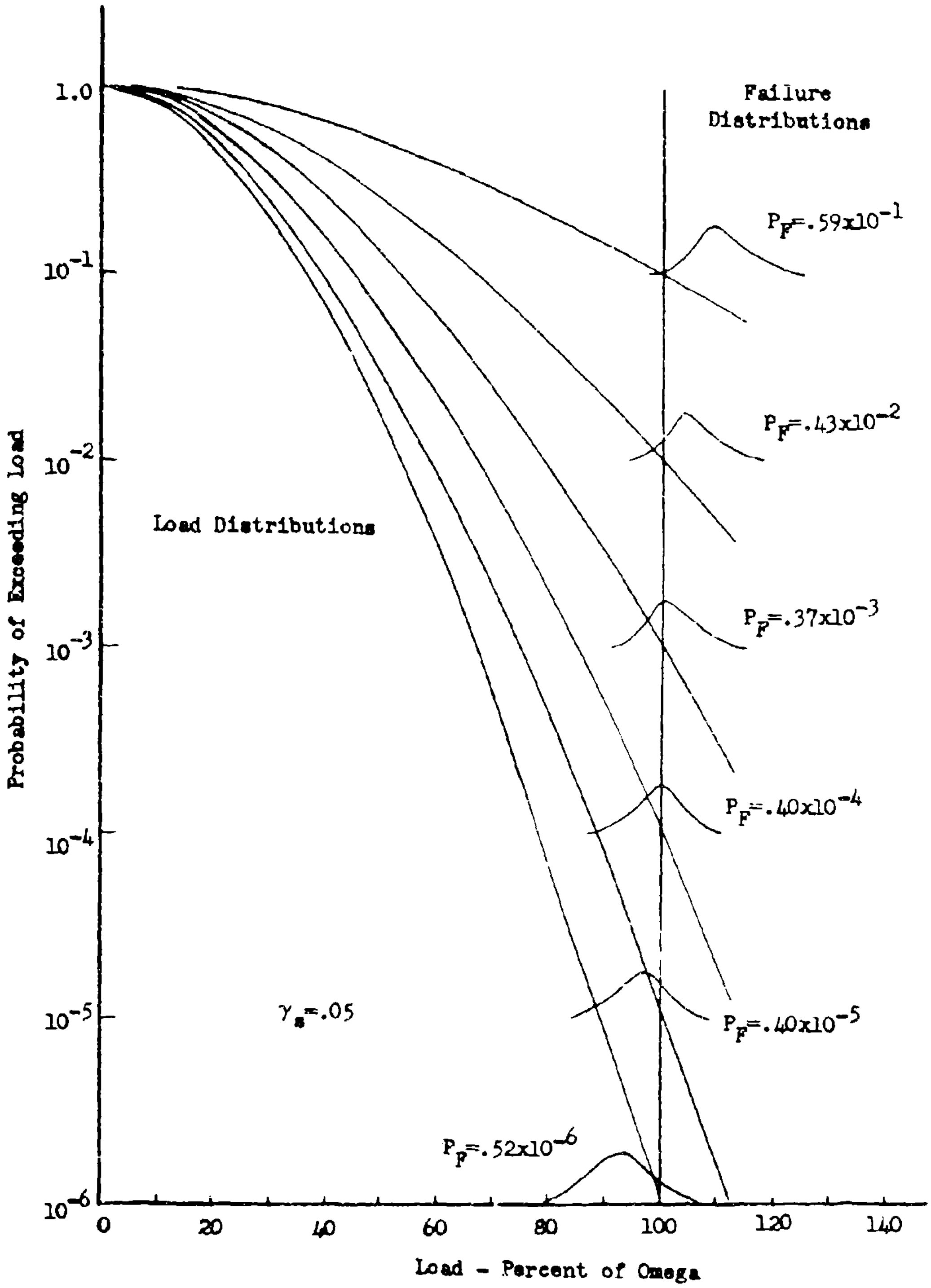


FIGURE 26. FAILURE DISTRIBUTIONS

The actual structural reliability attained in operations corresponds (to a first approximation) to the complement of the probability of exceeding the omega condition (P_{E_Ω}). Since P_{E_Ω} is controlled by vehicle operational results, this means that the true S.R. is almost completely determined by a function over which structural organizations have no direct control. This serves to explain the emphasis, as the philosophy of the proposed procedure develops, on establishing interface requirements with non-structural systems and on provisions to enforce these requirements. The point is made also that quantitative structural design criteria by statistical methods cannot be established unless consideration is given to operational conditions beyond specified limit conditions.

The disclosure of any error in the selection of the design conditions, particularly the omega condition, cannot be accomplished directly. For instance, if the predicted value of P_{E_Ω} is 0.0001, the actual value could be two orders of magnitude higher yet only one in a hundred vehicles would exceed the omega condition during the entire lifetime of the fleet. The chances of an exceedance early in the fleet life would be even less. If one single exceedance did occur, it would be difficult just from this single situation to decide whether there is an error in the prediction of P_{E_Ω} or whether the exceedance is one of the rare random exceedances that are to be expected.

What can be done is to compare whatever actual results are available with the predicted results. A few hours of flight experience that corresponds to the predicted values or less is not sufficient to "prove" that the predicted values are a satisfactory approximation of the lifetime values of a fleet of vehicles. But a relatively few hours of flight experience at a level significantly higher than the predicted values may be sufficient to decide that the predictions are wrong.

Figure 27 illustrates how such decisions can be made. The load factor spectrum that was predicted when the limit and omega conditions were chosen is shown. This represents the spectrum for the vehicle expected to operate for a lifetime of 20,000 hours. If the data on hand represents 200 hours of actual operations, the expected spectrum should have $\frac{200}{20000}$ as many occurrences at each load factor level as shown on Figure 27. If the actual 200 hour spectrum (Curve 1) were no more than three times (one-half order of magnitude) more severe than expected, there would be no concern. This variation would be considered to be in the expected range of variation at 200 hours. On the other hand, if the actual 200-hour spectrum (Curve 2) were 1000 times (three orders of magnitude) more severe than expected, it could be decided immediately that there was an error in the 20000-hour prediction. Note that this decision could be made from the available statistics after only one percent of the life shown, without the limit or the omega conditions being exceeded. Yet the decision that an error had been disclosed would be made by almost all concerned when the data makes the situation so obvious.

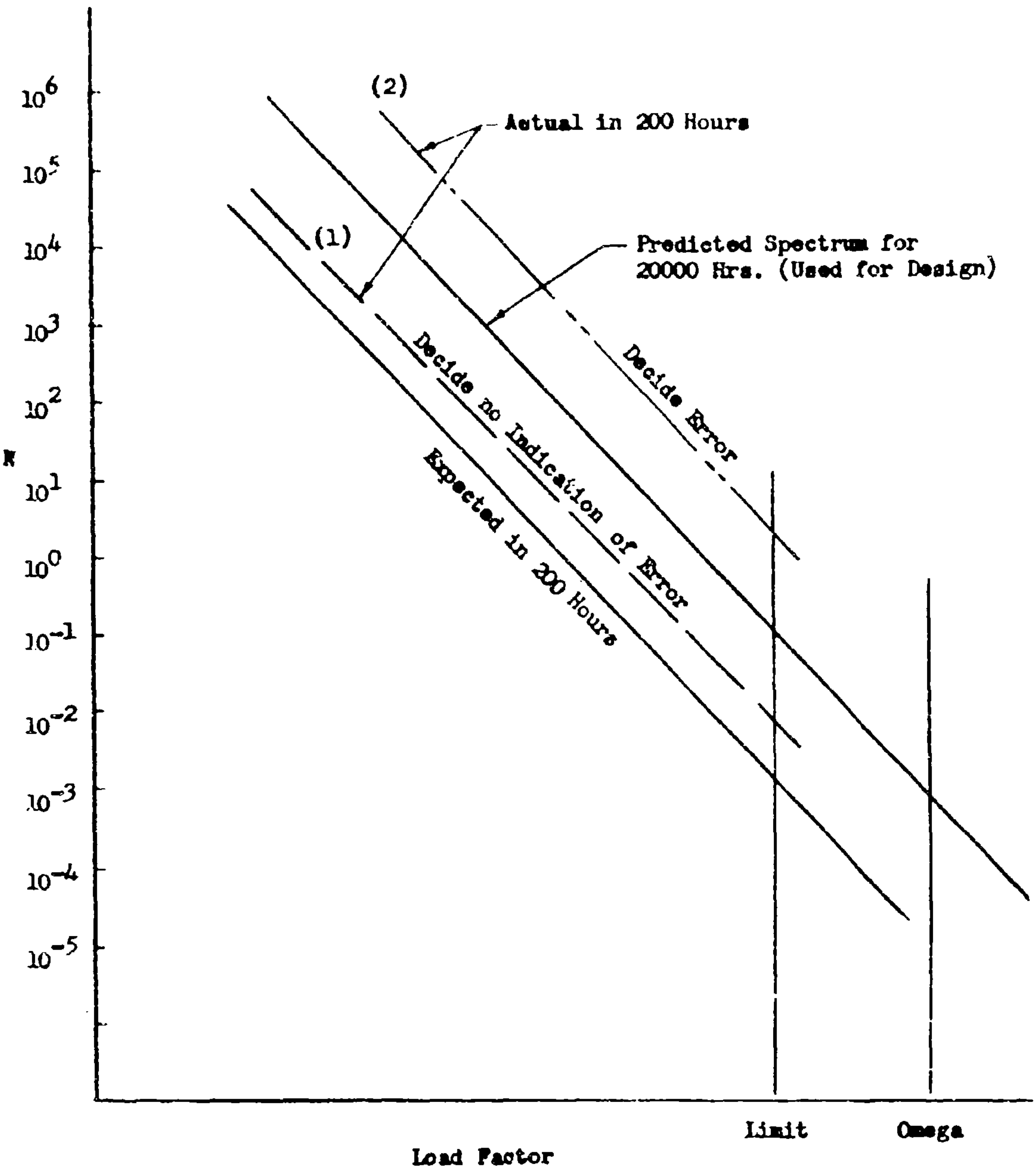


FIGURE 27. COMPARISON OF ACTUAL WITH PREDICTED SPECTRA

In a similar vein, it would be decided that there was something wrong with a landing impact velocity spectrum if the velocity that was predicted to occur once in a million landings occurred on the first landing.

Deciding that an error exists does not prove that the error exists. However, a sound engineering decision can be made on the basis just described. Therefore, the error-disclosure procedure can be based on a formalized decision-making mechanism using this basic approach. This approach was initially described in Reference 10. A more sophisticated version of the procedure has been incorporated in a study performed under the Reference 13 contract. In this manner, deterministic decisions can be made as to the acceptability of the specified limit and omega conditions.

g. Proof of Compliance

In the evaluation of the Present (Factor of Safety) Structural Design System in Volume I, the need for a proof of compliance procedure was emphasized. It was pointed out that a contract to produce a structural system under the Present System is administrable because the established proof-of-compliance procedures can resolve any disagreements. The evaluation of Volume I also stated that the principal deterrent to the adoption of a Purely Statistical Structural Reliability System is the lack of a proof of compliance technique. Therefore, it is considered mandatory that any new structural design procedure must be cast in such a form that explicit means are designated to prove compliance with the requirements of the SDC.

The proof of compliance procedure in the proposed method is essentially the error disclosure technique just discussed. If a structural system is analyzed first and then tested to disclose errors in the analysis, the structural system has proved its compliance with the requirements when the prescribed tests are completed satisfactorily with no errors being disclosed. Therefore, the proof of compliance consists of the application of the error-disclosing procedures just described for the strength of the system, the loads on the system, and the basic choice of the design conditions. These will be discussed in the same sequence normally followed in proving that a structural system complies with the requirements of the SDC.

(1) Strength

Proof that a structural system complies with the strength requirements is handled typically in three separate and distinct phases. First, the basic design is qualified and approved. Tests such as the conventional static tests, drop tests and fatigue tests are examples of design qualification. Second are acceptance tests and procedures for the individual structure. Proof tests are the obvious example of an acceptance test. Most individual vehicles are accepted on the basis of the usual quality control procedures without a proof test. Nevertheless, compliance with the specified quality control procedure corresponds to an acceptance test. Finally, there is always a form of proof of compliance during the operational life. This varies from a simple pre-flight check to overhaul and inspections. These all have as an objective the capability to certify or prove that the operational vehicle had sufficient structural integrity initially and has retained this structural integrity during the life of the vehicle.

The first phase, qualifying the basic design, should be handled in two parts. The first is to prove that the structural system will rarely, if ever, fail at the specified limit conditions. The second part is to prove that the structure has a capability to survive designated overload conditions beyond the specified limit conditions. The test loads for the first part of the proof of compliance for strength are defined as the loads corresponding to the specified limit condition multiplied by the limit test factor of safety determined from Figures 24 or 25. The effective purpose of this half of the requirement is the assurance that the structure will "never" fail at the limit conditions which by definition are permissible conditions. As a result of designing and testing the structural system to loads that are higher than the limit loads, by the factor indicated on Figures 24 or 25, it can be concluded that a random failure at the limit level or less will be suitably rare in proportion to the desired structural reliability. Furthermore, if a failure ever does occur at the limit condition, a discrete cause will have to be evident in terms of non-compliance with specific, deterministic requirements so that responsibility for the failure can be assessed and the corrective action will be obvious. Thus, the conclusion is appropriate that a structural system will never fail at conditions as low as limit conditions unless a gross, identifiable error has occurred in the fabrication or maintenance of the structure. The magnitude of the error that would cause a failure at limit condition or less is so great that it can be, and effectively has been by Figures 24 and 25, concluded that it is not feasible nor desirable to expect that the structure should tolerate and absorb such gross errors. Instead there is effectively a predetermination that it is feasible to fabricate and maintain the structure so that with reasonable care, considering the state of the art, such gross errors will not occur. The analytical computations leading to choice of the factors on Figures 24 and 25 are a prediction that the gross understrength represented by the difference between the test conditions and the limit conditions will not occur more often than established by Table I. But having once been made, the predictions can never be verified or proved. What can be done is to make decisions <u>based</u> on these predictions that a failure at a given level (1/LIMIT TFS) below the value established for design and test is not a structural responsibility but a fabrication or maintenance responsibility. Finally, even if enough statistical data is not available to perform the statistical computation accurately, the decision of what constitutes a gross error can be made with whatever information is available. Since no failures at limit or less are really acceptable, there must be an expectation that such gross errors resulting in an understrength can be prevented. The procedure should make explicit provision for defining how it is feasible to avoid the gross errors that will cause a failure.

If the feasibility of such avoidance cannot be documented and accepted by those responsible for such avoidance, then it does not appear justified to design and test the structural system to the level indicated by Figures 24 and 25. If this feasibility to avoid the gross error cannot be documented explicitly, it must be considered to be an indirect indication that the coefficient of strength scatter, γ_s, used to determine the limit TFS on Figures 24 or 25 must be unconservative and should be revised upwards.

The first requirement provided extremely high structural integrity for operational conditions up to and including the designated limit conditions because these conditions are, by definition, expected conditions. The purpose of the second requirement is to provide a reasonable capability to survive overload conditions beyond the designated limit conditions. Capability is needed up to and including the designated omega condition but no capability is needed beyond omega. It was explained previously that this capability to survive a properly defined omega condition is the real determinant of the total probability of failure and, thus, of the structural reliability. As noted in the evaluation of the Wagner procedure in Volume I, the concept that the structural design should consider omega (or ultimate) conditions is a break with the past. Some of the ramifications and problems associated with such an approach are discussed in Section VII.

The proof of compliance that the structural system will survive the omega condition and that the total probability of failure corresponds to the acceptable value is furnished in two steps. First, an analysis shows that the allowable is equal to or greater than the omega design load and then a test demonstrates that the structure can survive the omega design load. These two actions constitute proof that the structural system has the desired conditional reliability. The condition for the reliability is that the omega design loads correspond to the omega condition and that the probability of occurrence of the omega condition is no more than the designated value.

The test loads for the omega test are defined as the loads corresponding to the specified omega condition multiplied by the omega test factor of safety determined from Figure 12. It should be noted that, if the temperature of the omega condition is higher than for the associated limit condition, the test would be conducted at the omega temperatures. Also, the strength scatter, γ_s, might be larger at these higher omega temperatures. If so, the larger value should be used in determining the omega TFS rather than the smaller γ_s corresponding to the limit condition.

Survival of the omega test loads constitutes proof that the S.R. will be close enough to the desired S.R. to be satisfactory, provided that the omega condition and omega loads are correct. Proof of compliance for these two parameters must await the beginning of actual operations.

Successful completion of the limit and omega tests represents a deterministic requirement that is quite comparable to the requirements of the Present System. Although this discussion speaks of two sets of tests, limit and omega, in many cases engineering judgement will indicate that one or the other is much more critical so the less critical test will not be necessary. This is the same type of judgement currently used to reduce the test operation to a dozen or so of the most critical individual cases from what might be hundreds of potentially critical cases.

The limit and omega strength tests verify or prove that the basic design is satisfactory. This step is often termed design qualification. It is quite possible that the structural system of an individual vehicle from a properly qualified design may be deficient for any of a number of reasons. Typical would be a sensitivity to cracks in welds in tension or bonding difficulties

in composite structures. There are various forms of acceptance testing that constitute proof of compliance of an individual structure. A proof test to some small increment over the limit load might be very effective in increasing the structural reliability. This would be particularly true where loads beyond limit are very sharply truncated or non-existent. However, where the load spectrum is quite broad, proof testing may provide very little increase in reliability. For instance, a proof test to 105 percent of limit will help little in situations where the structure is loaded quite regularly to 125 percent of limit. In the future, it will be possible to use the Volume III computer program to determine the increment in S.R. due to various proof or acceptance test procedures.

After the structure has been designed, tested, fabricated and accepted by proper standards, the structure as it exists initially may be considered to possess satisfactory reliability. However, the structural strength may decrease during the operational life of the vehicle. Procedures should be considered on how to prove that the structural strength remains sufficiently high. Accidental damage, wear, fatigue, and creep contribute to possible strength decrements. In the past, ordinary maintenance care and visual inspections were sufficient to insure and prove that the structural strength remained sufficiently high. In the future, as time-dependent strength becomes more important, explicit procedures must be developed to serve as proof that the "now" strength of a structure is high enough. Some discussion of the problem is presented in Section 2.4.

(2) Loads

The proof of compliance procedure to show that the loads for limit conditions are satisfactory should be identical with present practice. As stated previously, it is considered that a properly conducted flight loads program will define loads close enough to the true value that experimental error need not be considered at this time. However, at some future time it will be desirable to add provisions to consider loads measurement errors to the computer program. This may be especially necessary as aircraft enter the hypersonic speed range and instrumentation difficulties increase.

Proof of compliance that the omega loads are satisfactory is one of the principal problem areas in implementing the proposed procedure. Some of these problems were discussed in Section 2.3e. At present it is considered that proof of compliance would consist of the analytical determination of the omega loads first. In questionable or non-linear regions the analytical calculation of the loads for specific omega conditions should be supplemented by wind-tunnel tests. The proof of compliance supplied by flight test measurements will necessarily be indirect and incomplete. Nevertheless, it can be a very explicit requirement. For instance, the measured load up to the vehicle limitations should compare very closely with that predicted analytically and from wind-tunnel results. This establishes that the basic analytical method is correct and reduces any possible error to the range between limit and omega conditions. Furthermore, it is possible to determine trends such as the variation of load with load factor, dynamic pressure, angle of attack and Mach number. Cross plots and extrapolation of these trends will be sufficient to verify the omega loads in most cases.

(3) Design Conditions

Proof of compliance procedures for the design conditions cannot begin until operations with the vehicle actually begin. Proof of compliance in one form or another actually should continue throughout the life of the vehicle. The first formal indication or proof that the choice of design conditions might not be satisfactory will come from the pilots or users of the vehicle. If the vehicle cannot be operated without exceeding the operational limitations rather frequently, the limit condition is undoubtedly too low and possibly the omega condition, as well. By definition the limit condition should be one that is rarely exceeded during the lifetime of the vehicle. Hence, if it has been exceeded a number of times during the early life of the vehicle, a decision can be made that limit condition has been exceeded too often. How often is "too often" can be decided by procedures such as described in Section 2.3f.

In addition to the simple reporting of exceedances of the operational limitations, the proof that the design conditions were chosen properly for the actual vehicle operational conditions can be obtained from any of various forms of flight recorders. Eight-channel recorders, VG or VGH recorders, and statistical counters can be used to verify the design conditions. If the number of exceedances of a given parameter is higher than some value, predetermined by methods described in Section 2.3f, it can be decided that the design conditions are not compatible with the operations. The procedure developed under the Reference 13 contract will analyze operational data and print warnings if the operational usage is more severe than it should be.

If the decision is made that the design conditions are being exceeded too frequently, three courses of action are available. First, the vehicle user can be informed that the usage of the vehicle is exceeding (or potentially exceeding) the intended usage for which the vehicle was designed. Changes in operations can correct the situation before any failure actually takes place. Second, the user can decide that the current vehicle usage is necessary and will be continued in the future. In this case, it would be necessary to establish new design conditions and redesign the structural system accordingly. The third alternative is to decide to continue the more severe operational usage without change and without redesign. In this case the structural reliability that was originally selected as the goal will not be attained. The program from Volume III can be used to recompute a new S.R. associated with the actual data on operational usage. The user can be informed as to the failure rate that can be expected if the operations continue to be as severe in the future.

h. Determination of Cause of Operational Failure

In case there is ever a failure in the structural system during vehicle operation, the determination of the cause will be very comparable to the procedure in the Present System as described in Volume I. If the accident investigation can establish that the failure occurred at less than the limit condition, the decision can be made without equivocation that the cause of the failure is a deficiency or error somewhere in the structural system. If the failure occurred when the vehicle was operating at or beyond the omega

condition, the structural system can have no responsibility since it has completely complied with its requirements. The accident must be considered to be the result of overloading the vehicle to grossly more severe conditions than established as permissible in the operational limitations.

Although the causes of the structural failure will not be quite so clear-cut if the failure occurs somewhere between limit and omega conditions, a decision as to the "cause" can be made. First, the structure must have a discrepancy present ranging from a minor to a major error. It was intended in the design of the structural system that 99 out of 100 (or a similar number) of the operational vehicles should survive up to the omega condition. Therefore, when a failure does occur at less than the omega condition, it is far more likely that the failure results from an error in the structural system than from a random low strength in a structure properly designed, tested, fabricated and maintained. Therefore, a decision can be made that a structural deficiency is at least a contributing cause to any failure between limit and omega conditions.

On the other hand, any operation of any amount beyond the limit conditions as specified in operational limitations is impermissible. Therefore, if a failure occurs anywhere between limit and omega conditions, the user must be considered to have contributed to the failure by overloading beyond the permissible limits.

As a result of this capability to determine a cause of failure, responsibility for causing the failure can be assessed and the corrective action necessary to prevent a repetition of the failure can be determined. This can be done because both the design and operational requirements are associated with deterministic limit and omega conditions even though the original choice of the conditions was based on statistical considerations.

2.4 TIME-DEPENDENT (FATIGUE) STRENGTH SITUATIONS

a. Basic Structural Reliability Considerations in Fatigue

The discussion in Section 2.3 dealt with what is commonly called the static situation. The loads may actually be dynamic in nature as in gust or landing situations but failure is caused by a single application of a large load. An implied corollary of static design is that the structural strength is a time-invariant function. If the strength does not change during the vehicle's lifetime, the failure is dependent only on whether the specific failing strength is exceeded at any time during the life of the vehicle. In many structural systems the strength is a time-dependent function. Fatigue represents the obvious time-dependent situation but hot structure and corrosion effects also involve time-dependent functions. The present study is based upon fatigue considerations but the philosophy developed for this type of structural environment is universal in its application to any time-dependent strength problem.

The approach used in developing the proposed new structural design criteria for fatigue situations involves fundamentally different considerations from those used in most other fatigue analysis procedures. The

principal difference is use of the concept of residual strength as the significant fatigue parameter rather than life. "Life" is not a physically meaningful concept in fatigue analysis. As stated in Reference 11, "Fatigue failure is, in essence, an ultimate load failure, but one involving a fatigue-damaged structure, and therefore, occurring under a terminal load of considerably lower intensity." No structure ever failed mechanically simply because it exceeded some number of hours of operation. If low loads were being experienced when the "life" was exceeded, as in a navigational training flight in an airplane, the structure would not fail. When a high load immediately before or immediately after the supposed end of "life" is experienced, the structure will fail. Failure must always be the result of the load at that particular instant of time exceeding the strength at that particular instant of time. Just as the initial strength in a group of similar structures will vary, so will the residual strengths of these same structures vary at a later time during the life of the structure.

The probability of failure of a structure during some particular period during its life is a function of the residual strength distribution at that particular period and the load distribution during that particular period. This is analogous to the definition of the probability of failure when the strength does not vary during the lifetime in the static strength situation. In Section 2.2 of Volume III this probability is defined as

$$P_F = \int_0^\infty P_{E_L}(x_1) p_{25}(x_1) dx_1 \tag{7}$$

This is the conventional formulation of the probability of failure except that the strength density function (p_{25}) is expanded in meaning to include a probability of analytical error and probability of test disclosure of this error. This formula is the basis for all of the analyses of the static cases presented in the previous section. This same formulation is used in the fatigue analysis, but the functions are time-dependent for fatigue. If it is assumed that the strength distribution is constant for some small period of time, $\Delta\tau$, at a time τ, the formulation for the probability of failure during this $\Delta\tau$ period parallels equation (7).

$$P_{F_K}(\tau, \Delta\tau) = \int_0^\infty P_{E_L}(x_1, \Delta\tau) p_{RS}(x_1, \tau) dx_1 \tag{8}$$

where

$$\tau = K\Delta\tau \tag{9}$$

The form of equation (8) is the same as equation (7). The period for which the strength distribution $p_{25}(x_1)$ in equation (7) is assumed constant is for a vehicle lifetime, such as 5000 or 50,000 hours. In equation (8), the strength distribution p_{RS} (x_1, τ) is considered to be constant for $\Delta\tau$ period, but it is different at each time, τ, such as at 5, 50 or 500 hours. In the same vein,

$P_{E_L}(x_i, \Delta\tau)$ is the probability that the load will exceed x_i during a short time period, such as 2 or 200 hours, whereas $P_{E_L}(x_i)$ in equation (7) is the probability of exceeding x_i at any time during a lifetime period such as 5000 to 50,000 hours. Equation (8) reduces to equation (7) if P_{RS} is a constant for any time τ and if $\Delta\tau$ equals the total hours in the vehicle lifetime.

Equation (8) expresses the probability of failure during the k-th time period, which is some time between zero time and the specified service life, T. Therefore, the total probability of failure at time T can be written as

$$P_F(T) = 1 - P_S(T) = 1 - \prod_{k=1}^{\frac{T}{\Delta\tau}} P_{S_K}(\tau, \Delta\tau)$$

$$= 1 - \prod_{k=1}^{\frac{T}{\Delta\tau}} \left[1 - P_{F_K}(\tau, \Delta\tau)\right]$$

$$= 1 - \prod_{k=1}^{\frac{T}{\Delta\tau}} \left[1 - \int_0^{\infty} P_{E_L}(x_i, \Delta\tau) p_{RS}(x_i, \tau) dx_i\right] \qquad (10)$$

The capability to evaluate equation (10) is critically dependent on the ability to evaluate the residual strength function p_{RS}. However, the difficulty in evaluation does not detract from the fact that the fatigue probability of failure, as formulated in equations (8), (9), and (10), is a physically satisfying and mathematically sound formulation of the problem.

Much of the technical effort in analyzing fatigue problems has been based on the concept of fatigue life. Therefore, there is not extensive literature available on the determination of residual strength. Valluri, in Reference 12, presented a fatigue analysis that is adaptable to the needs of the proposed criteria procedure. The details of the adaptation of Valluri's procedure to the computer program used to solve equation (10) are presented in Volume III of this report. It should be understood the formulation of equation (10) is not dependent on the particular residual strength functions developed in Volume III from the theory of Reference 12. If a more accurate prediction can be developed or if experimental data on residual strength can be obtained, the program presented in Volume III will change in detail but not in principle.

The essence of the Volume III adaptation of the Reference 12 theory is the relationship between the Fatigue Damage Index (FDI) and the Residual Strength (RS). The FDI is a convenient concept, somewhat analogous to the well known Miner's Fraction. This analogy is developed more completely in Volume III. However, the meaning of the FDI is associated with RS so that the greater the fatigue damage, as indicated by the FDI, the less the residual strength. The relationship is nonlinear but simple to determine. The FDI for a simple case of constant amplitude loading increases linearly with time according to the Volume III discussion. The relationship between FDI and RS is given in Volume III as

$$\mathrm{FDI} = \log_e \frac{\sigma_{ult}}{\sigma_{RS}} \tag{11}$$

Thus, a typical relationship would be as shown in Figure 28. It is indicated in Volume III that the increase of the FDI will be approximately linear when a random loading is the source of the fatigue damage. Again, this is similar to the growth of Miner's Fraction with time. Therefore, in the development of the proposed procedure, it is assumed that the growth of the FDI is always linear.

b. Rudimentary System

The use of the FDI/RS relationship in structural design criteria based on statistical methods can best be illustrated by a simple example. The parameters in the example are deliberately chosen to produce a high probability of failure so the numbers will be more comprehensible than they would be with the very low values usually considered in structural reliability problems.

It is assumed that the loading spectrum for a vehicle with a nominal 20,000-hour service life is as shown on Figure 29. It is then assumed that the structure is such that this loading spectrum produces the fatigue damage and residual strength shown on Figure 28. In the real situation, the FDI would be computed from the load spectrum and knowledge of the structure as discussed in Volume III. A more realistic example, using F-100 data, is presented in Section VI of this report. To simplify the manual calculation of the probability of failure, the RS is assumed to vary in steps every ten percent of the 20,000-hour life, or in 2000-hour increments as shown on Figure 28. A 2000-hour load spectrum can be determined from the 20,000-hour spectrum as shown in Figure 29, assuming that the 2000-hour spectrum has 1/10 the number of exceedances of the 20,000-hour spectrum. From this 2000-hour spectrum, the probability of exceeding a load x_1 can be calculated using the conventional Poisson distribution.

$$P_{E_L}(x_1) = 1 - e^{-N} \tag{12}$$

This probability is also shown on Figure 29. Finally, it is assumed that all structures will experience identically the same fatigue damage or loss

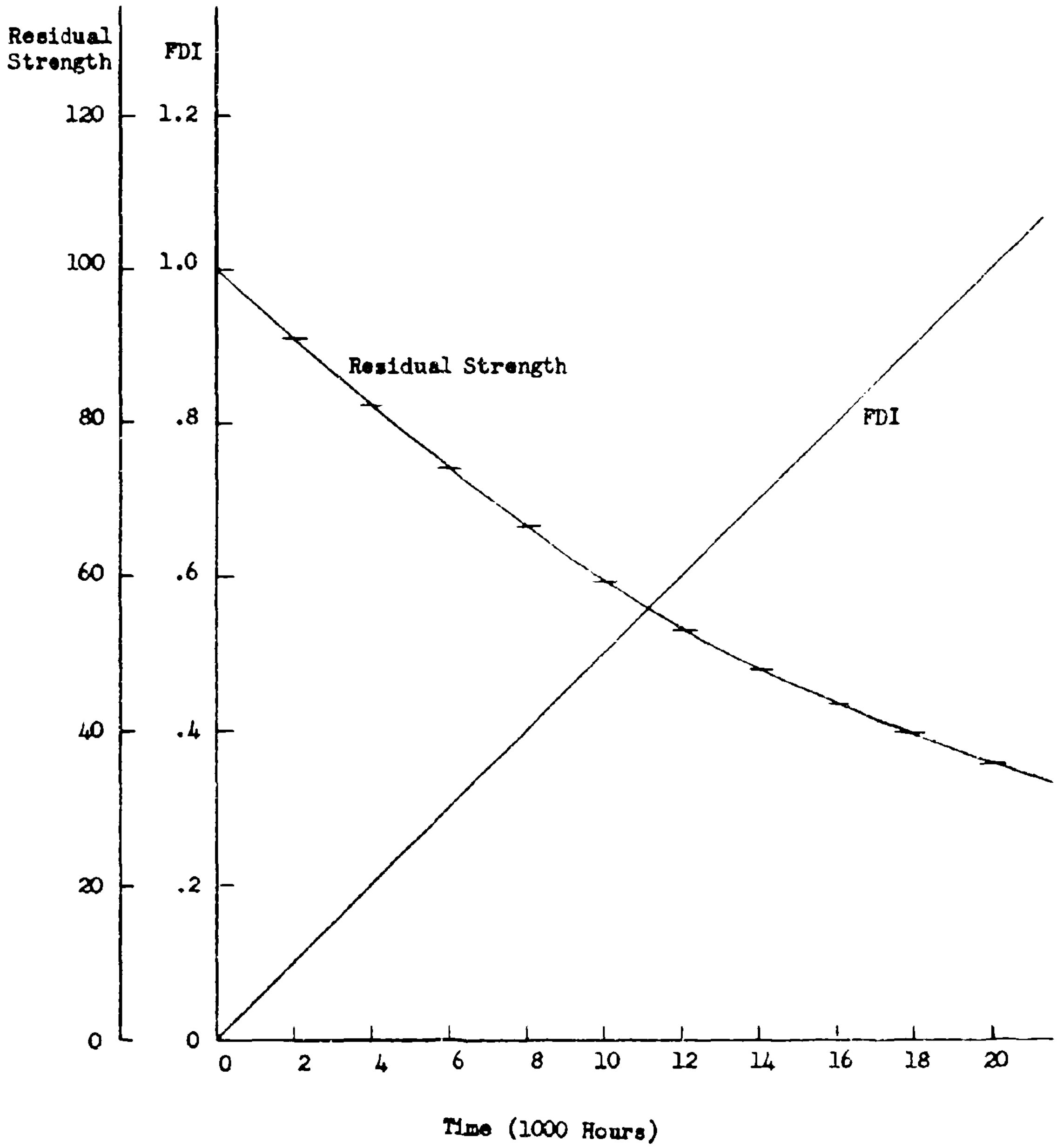


FIGURE 28. RESIDUAL STRENGTH AND FDI

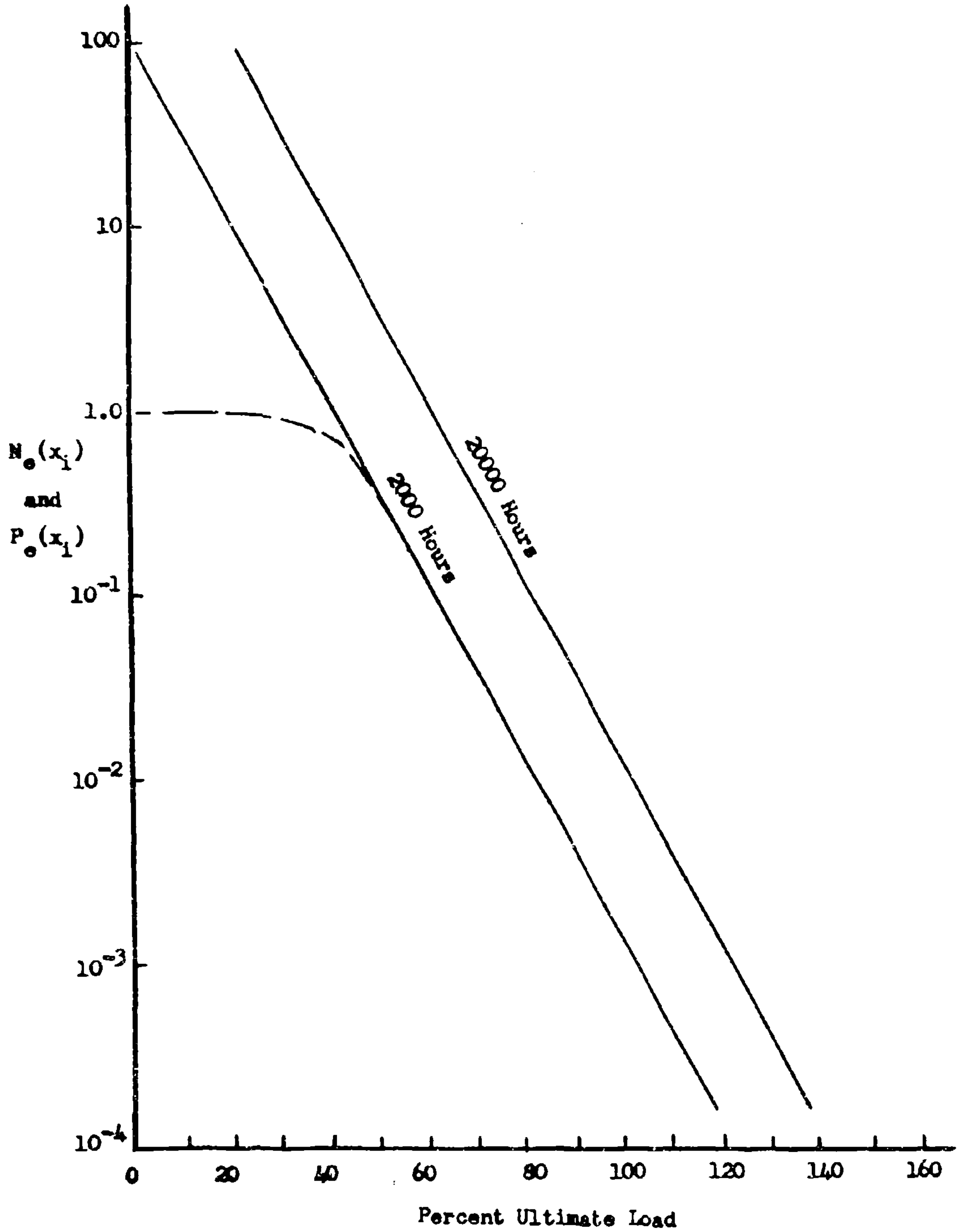


FIGURE 29. LOAD SPECTRA

in residual strength. It is recognized that all these assumptions oversimplify the problem, but they serve the purpose of illustrating that there is no single time that can be called the life of the structure. The assumptions will be expanded and justified later in the discussion after the basic approach is presented.

Since it was assumed that there is no scatter in the strength of the individual systems, equation (8) reduces to $P_{F_K} = P_E[RS(K)]$. In the first 2000-hour period, the value of the average residual strength from Figure 28 is 96 percent of the initial ultimate strength. From Figure 29 the probability of exceeding this load during the 2000-hour period is 0.0018. Thus, the probability of survival of the period is 1 - 0.0018 or 0.9982. During the second 2000-hour period, the strength has dropped to 87 percent and the probability of exceeding this strength has increased to 0.0063. The probability of surviving this second period becomes 0.9937. The probability of surviving both the first and second 2000-hour periods is the product of 0.9982 x 0.9937, or 0.9919. The procedure is continued for as many periods as desired. Table II presents the numerical data and Figure 30 shows the plot of the probability of failure. Figure 31 shows the same data plotted on a linear scale which better shows the time span where failure might be observed in operations. Figure 31 also shows a histogram of the percentage of structures that would be expected to fail in each period. Typically, if 10 to 100 structures were involved, the spread in life about the mean would be approximately two to one as shown.

Another phenomenon that can be illuminated by this simplified example is the difference between service failures and test failures. If the spectrum shown on Figure 29 for 20,000 hours is used for the fatigue test, the applied spectrum must be a truncated spectrum. A load cannot be applied one-tenth of a time during the test of a single test article. Therefore, a spectrum such as shown on Figure 29 would result in the limit load of 100 percent being applied once sometime during the test. No higher load would be applied.

This truncation of the higher loads would not affect the fatigue damage significantly but would make a major difference on when the structure will fail during the static test relative to the failures that would occur in service. Many different plans for determining the maximum load applied during each sub-period are reasonable. The shaded lines on Figure 32 show one such plan for applying test loads that is consistent with the spectrum of Figure 29. With this particular arrangement, the test load in each period would be less than the residual strength so no failure would occur until the 55 percent load was applied during the eighth period. Contrast this with a significant number of failures beginning in the third period of the service operations of a fleet as shown on Figure 31. If 100 vehicles had completed 30 percent of the nominal life, Table II shows that two or three (2.6%) of the vehicles would have experienced a load high enough during this third period to cause a fatigue failure. Yet no failure would occur during the test until the eighth period or 80 percent of the nominal life. From Figure 32 it can be seen that, if the [illegible]imum test load (67%) happened to be applied during the fifth period instead of during the

TABLE II

PROBABILITY-OF-FAILURE GROWTH

2000 Hour Period	Average Strength Fraction	Probability of Exceeding Load Corresponding to Strength	Incremental Probability of Survival ΔP_S	Cumulative Probability of Survival πP_S	Cumulative Probability of Failure P_F
1 st	0.96	.00183	.9982	.9982	.0018
2 nd	0.87	.0063	.9937	.9919	.0081
3 rd	0.79	.017	.982	.974	.026
4 th	0.71	.056	.944	.919	.081
5 th	0.64	.125	.875	.804	.196
6 th	0.57	.25	.75	.603	.397
7 th	0.51	.40	.60	.362	.638
8 th	0.46	.56	.44	.159	.841
9 th	0.42	.67	.33	.052	.948
10 th	0.38	.77	.23	.011	.989

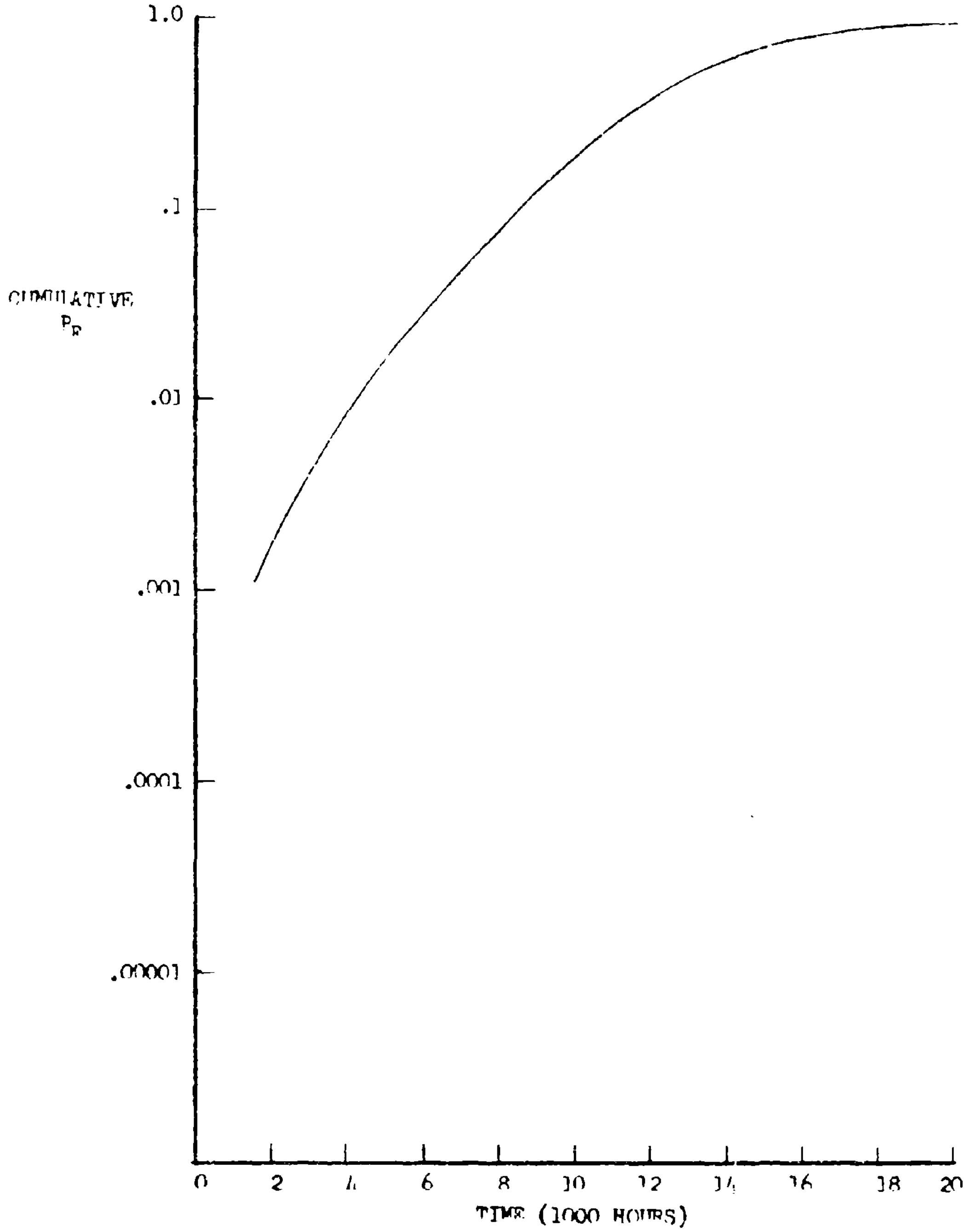


FIGURE 30. CUMULATIVE PROBABILITY OF FAILURE

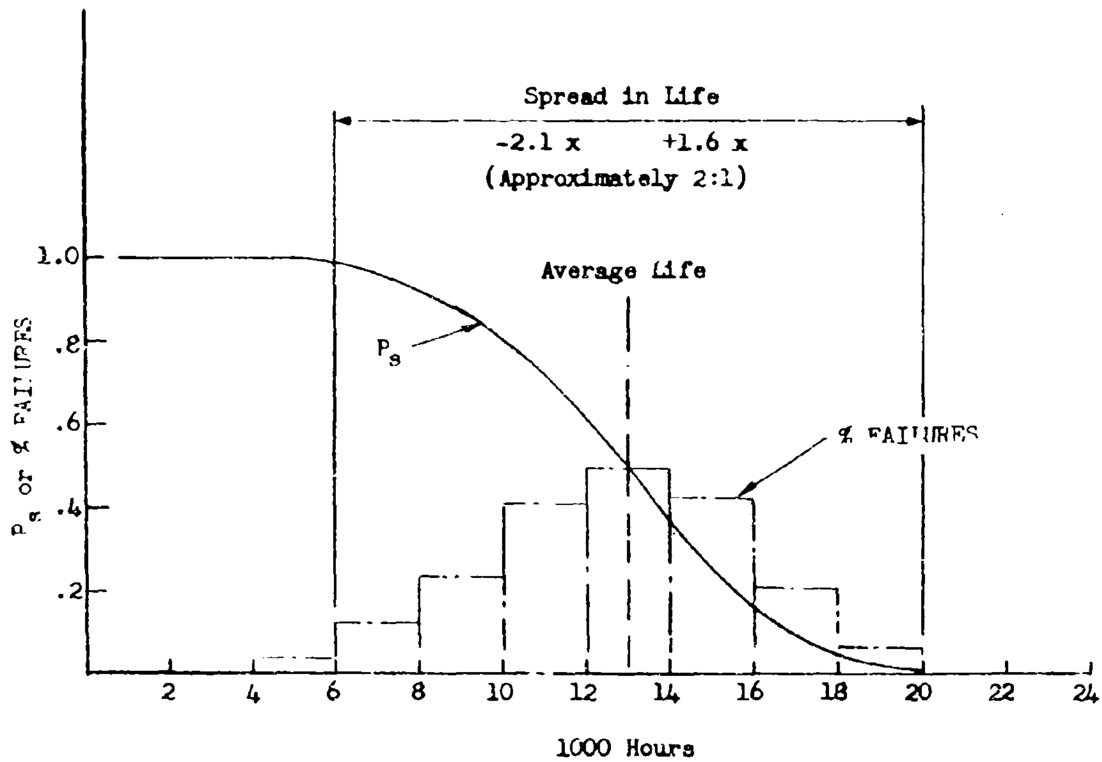


FIGURE 31. DISTRIBUTION OF FATIGUE LIF

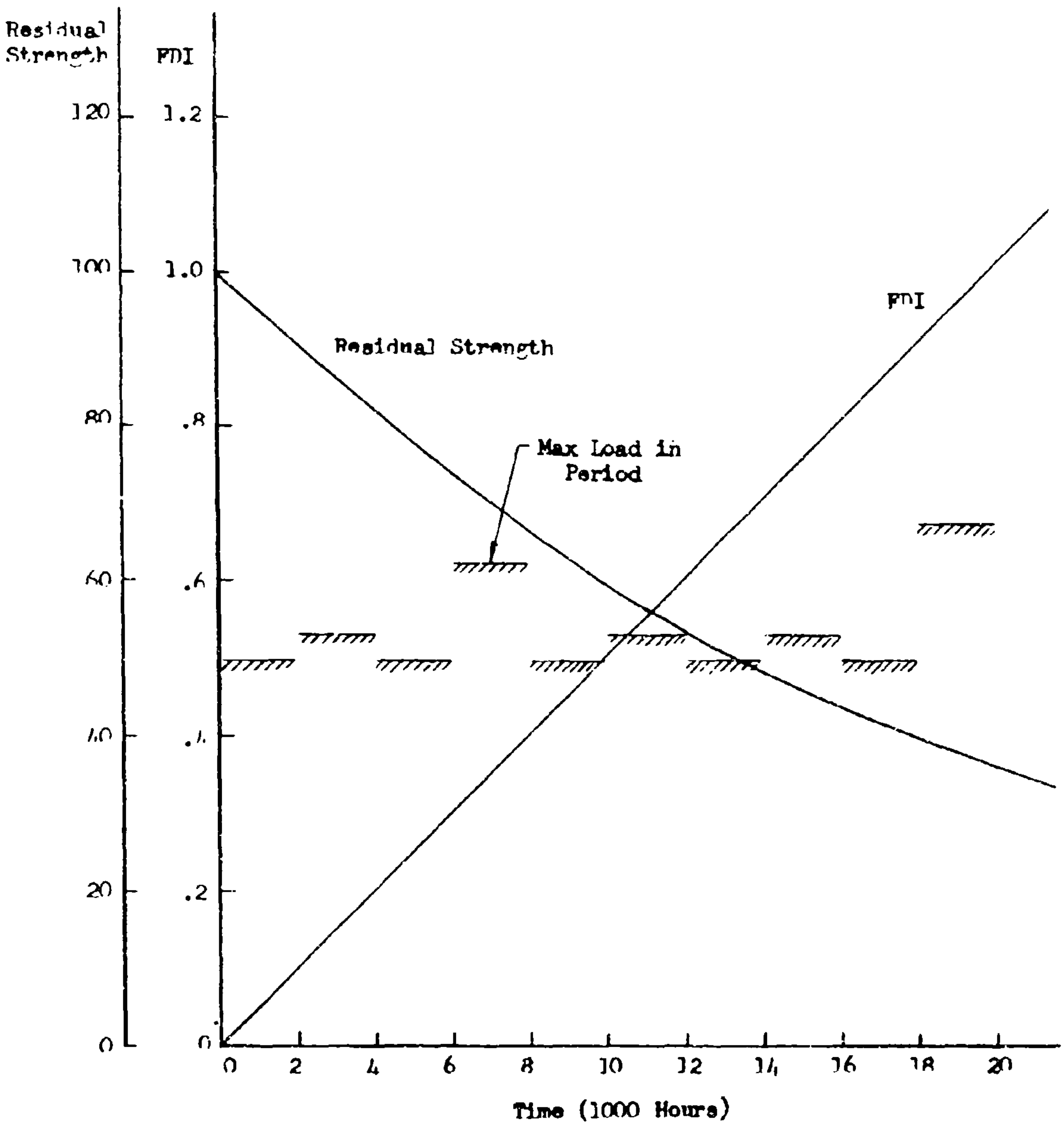


FIGURE 32. EFFECT OF RESIDUAL STRENGTH TESTS

tenth period, test failure would occur during the fifth period instead of the eighth. On the other hand, if the fatigue damage were slightly less, the failure would not occur in the fifth period, even with the 67 percent load applied. Then, with the higher RS, no failure would occur until after the tenth period.

Thus, without considering that there is any variation between individual structural systems, it can be shown that a test failure may occur anywhere between 9000 and 20,000 hours. In the example, significant numbers of failures would occur in a fleet between 4000 and 6000 hours and by some standards as early as 2000 hours. It is considered that this wide discrepancy between time of test failure and the beginning of fleet failures is a gross indication of why most previous fatigue criteria have considered that a scatter factor is necessary to relate permissible service life to the fatigue test life. It must be emphasized that the scatter between test and service failures in this example are not necessarily realistic since the fatigue damage was deliberately assumed very large to help illustrate the considerations essential to this type of analysis.

c. System with Scatter in Residual Strength Considered

The first refinement of the Fatigue Reliability Program (FATREL) described in Volume III beyond the simple formulation just described is the introduction of the effect of scatter on the residual strength. Two additional parameters are introduced into the calculation to define this scatter as a function of time. These two parameters are the coefficient of strength scatter at time zero, γ_s, and the scatter factor on fatigue life, s. γ_s is the same scatter factor discussed in Section 2.3. The fatigue scatter factor, s, represents the range in hours or number of cycles to failure relative to the mean life. This factor is discussed further in Volume III.

When these two scatter parameters are added to the previous definition of the FDI, or residual strength, the complete lifetime strength distribution is defined. This is shown on Figure 33. Points (A) and (B) define the line representing the mean strength. This is the same FDI line shown on Figure 28. Point (A) represents the initial mean strength at time zero. Actually, this is calculated from Point (C) which represents the "allowable" strength, knowing γ_s. In the example, this allowable represents the 99-percent-exceed stress. From the mean stress at Point (A), the one-percent-exceed stress (D) is calculated. The values at points (A), (C), and (D) are inputs to the program described in Volume III.

The variation in the residual strength distribution with time is controlled by the fatigue scatter factor, s. This factor represents the variability in time (or number of cycles) when nominally identical structures fail under constant amplitude loading. There are data in the literature showing that such scatters range at least over the range of 2:1 to 10:1. It should be understood that this scatter is not the same scatter discussed in connection with Figure 31. In that example, there was no scatter in the strength of individual structures. The decrement in the RS

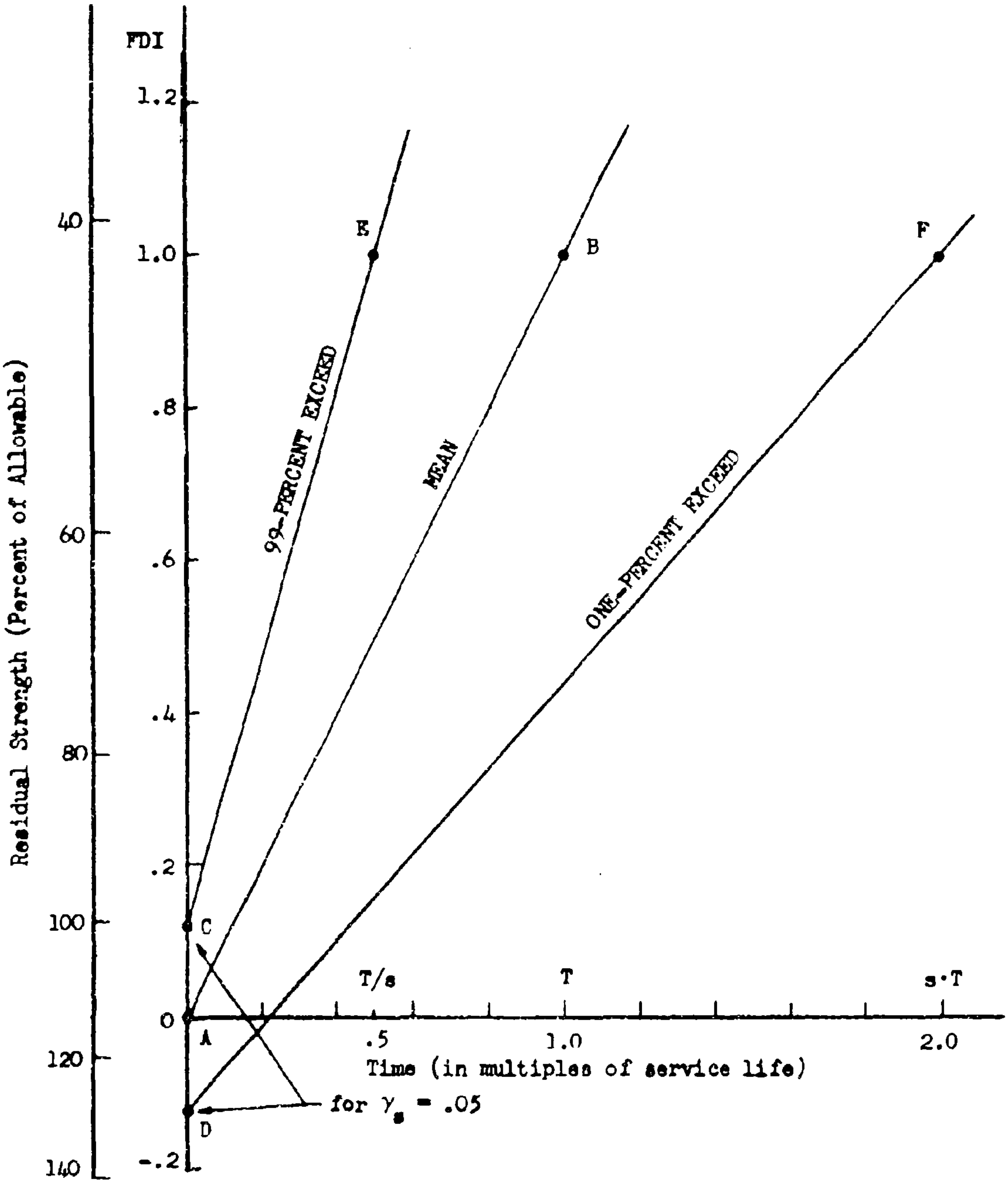


FIGURE 33. FDI DISTRIBUTION

of each structure was assumed to be identical in all the structures. The scatter in the time of failure was due completely to the randomness of the application of loads large enough to exceed the RS of the structure to which they were applied.

If the scatter in time of failure under application of constant amplitude loading is considered to be a known parameter, it can be incorporated in the computation. Furthermore, it is considered that the meaning of a scatter factor of 2.0 is that 99 percent of the structures survive at least to one-half the mean time to failure and one percent survive to twice the mean time to failure. It is assumed that this scatter in life is applicable when the residual strength corresponds to approximately 40 percent of the ultimate tensile strength. This residual strength corresponds to a FDI = 1.0. Accordingly, points (E) and (F) on Figure 33 can be located on the FDI = 1.0 level with Point (E) at one-half the hours for Point (B) and with Point (E) at twice the hours. The three lines on Figure 33 are the basis for constructing the complete RS distribution. Similar lines for a given probability of exceeding the strength are drawn as shown on Figure 34. The calculations for each of these lines is performed automatically in the computer program described in Volume III.

With the residual strength distribution established for a given time period from Figure 34 and the probability of exceeding a load established as on Figure 29, Equation (8) can be evaluated for each time period. Then, the cumulative probability of failure can be determined by evaluating Equation (10). The FATREL program described in Volume III performs all of these calculations automatically. The program prints out the incremental probability of failure for each time period and the cumulative value.

d. System with Errors in Fatigue Analysis Considered

Up to this point in the development of the philosophy governing the proposed procedure for structural design criteria for fatigue situations, it has been assumed that the strength distribution, p_{RS}, was known, i.e., that there were no errors in the fatigue analysis. As it was pointed out in Section 2.3c, there are many cases where the actual strength of a structural system is different from that predicted by analytical calculations made during the design of the system. Figure 5 presents data from Reference 6 documenting the incidence of such discrepancies. There are no known data available to compare the predicted results from fatigue analyses with the actual results from tests. The fatigue analysis of a structure is a more complex problem than the static analysis so it might be expected that the number of discrepancies would be greater. It is well known that there has been a considerable incidence of premature failures during fatigue tests. Therefore, it must be considered that the frequency of occurrence of such discrepancies, or errors, in the analysis is not infrequent.

There are a number of different causes for errors in a fatigue analysis. However, each cause, such as a higher stress concentration factor (SCF) than anticipated, a generally higher stress level or a material more sensitive to fatigue, would result in a higher FDI. This, in turn, would result in a

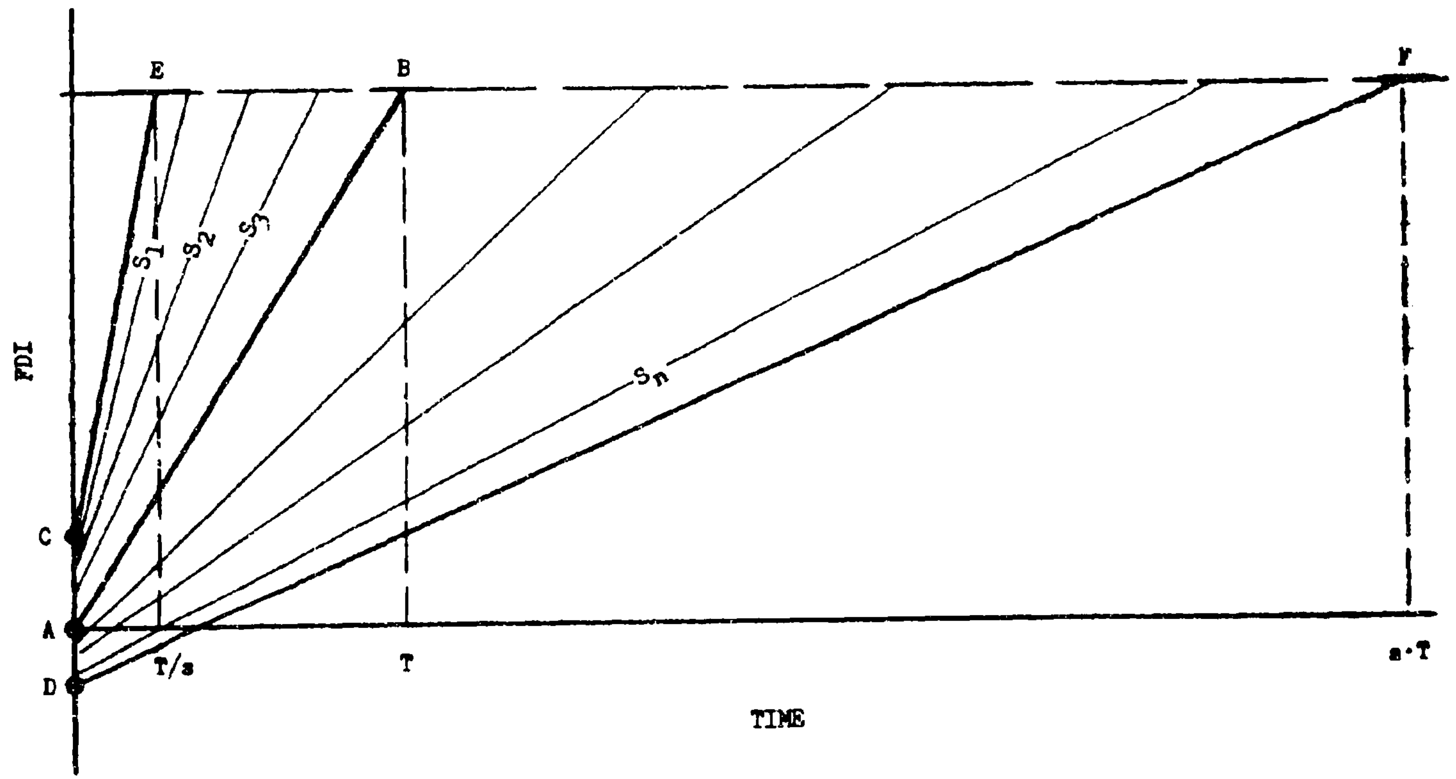


FIGURE 34. STRENGTH DISTRIBUTION AS A FUNCTION OF TIME

higher probability of failure. Figure 35 presents a plot showing the higher P_F that results from a higher SCF. Thus, if the analyst assumed no stress concentration, he would predict that a service life of 6800 hours would result in the desired SR of 0.99. However, if a 4.0 SCF happened to exist unbeknownst to the analyst, the life for 0.99 SR would be about one third as much or 2300 hours. If a series of structures were designed with the intention that there be no stress concentration but if 25 percent of the designs had an unpredicted 4.0 SCF, the average failure rate for a 6800 hours life over a group of such designs would be 0.75 x .01 + 0.25 x 0.99 = 0.2550 instead of the 0.01 that follows if all designs are as predicted. Almost all of these failures would be in the 25 percent that have the high probability of failure. This is very analogous to the situation described in Section 2.3c and shown on Figure 9. There, the structural designs with lower than predicted mean strengths contribute the most to the total failure rate of all the systems from A through T.

The computer program described in Volume III has the capability to accept six different stress concentration factors and an associated occurrence density figure (corresponds to 0.75 and 0.25 just discussed). This is considered sufficient to define the range of possible discrepancies in actual fatigue damage relative to the value predicted analytically.

e. Fatigue Strength Error Disclosure by Testing

In Section 2.3d it was pointed out that one strength test could not "prove" the reliability of a structure but that one test could disclose errors in the analysis. The same principles apply to structural design when fatigue is a major consideration. The problem in the fatigue situation is that a single fatigue test does not have the same certainty of disclosing an error as has a single static test of a structure with a narrow strength scatter.

An example of the difficulty in establishing a fatigue test that will reveal errors in the fatigue analysis with a high degree of certainty can be seen by examining Figure 35. Suppose that a 0.9999 SR is desired at a service life of 3000 hours. If the structure has a probability of failure as represented by the lower curve of Figure 35, the P_F of 10^{-4} at 3000 hours will correspond to 0.9999, as desired. However, if there is a higher than expected SCF (or anything else that increases the fatigue damage) as might be represented by the higher curve on Figure 35, the P_F at 3000 hours will be 4×10^{-2}. This is $2\frac{1}{2}$ orders of magnitude higher than the desired value. If a design which corresponds to this upper curve is tested to 6000 hours (twice the number of hours corresponding to the nominal service life), the probability of failure is 0.95. This means a probability of 0.05 that the "unreliable" design will successfully pass the test to twice the nominal life. Accepting one out of every twenty deficient designs would not be tolerable in most cases. The power of the fatigue test as a discloser of error would be grossly inferior to that provided by the static test as discussed in Section 2.3d.

The previous paragraph discussed the problem of the relatively high chance of accepting structures that will fail much earlier than predicted. In addition to this problem there is the problem that the test spectrum cannot represent the service spectrum exactly. Any load that has a frequency of

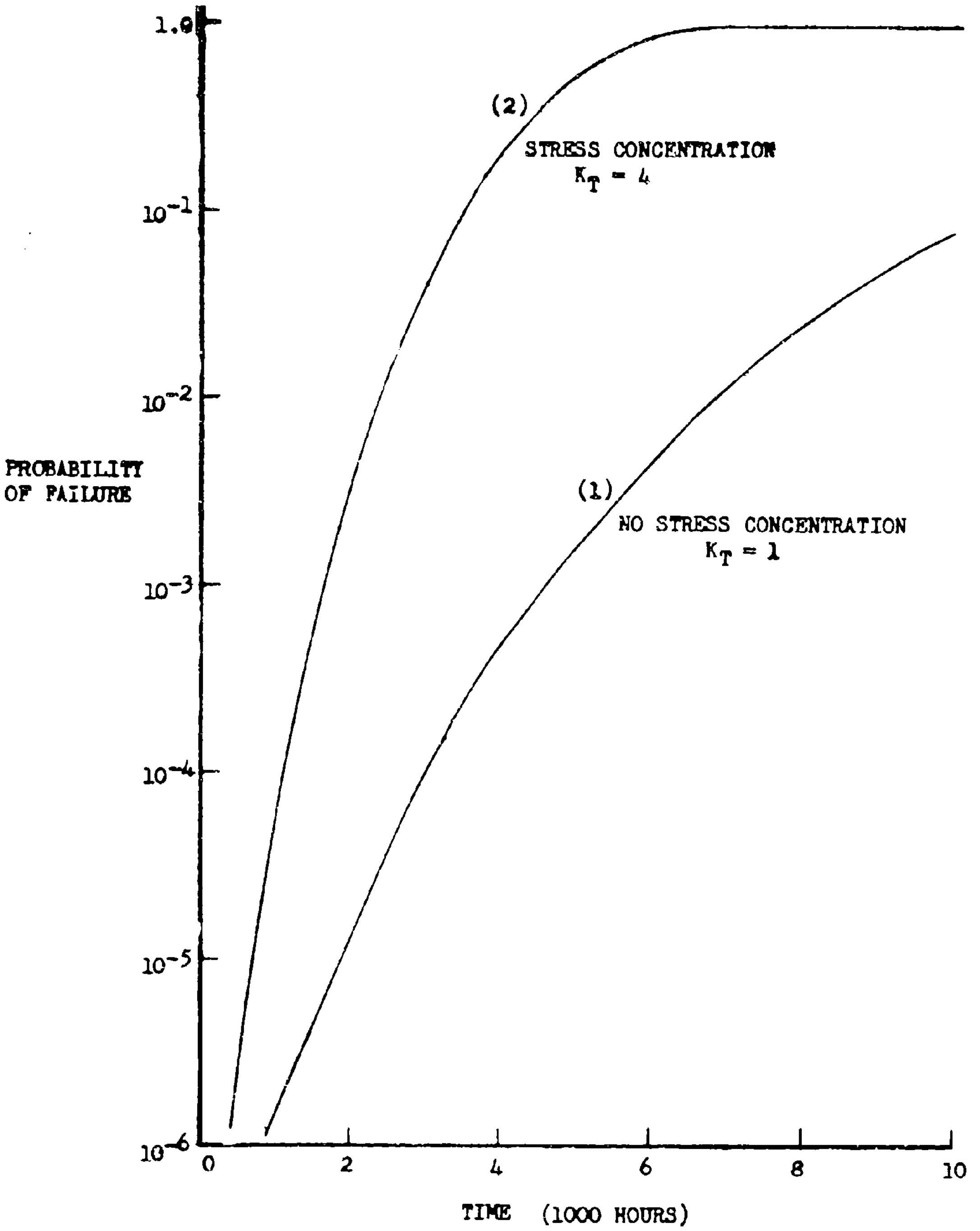


FIGURE 35. EFFECT OF STRESS CONCENTRATION ON PROBABILITY OF FAILURE

occurrence less than 1.0 would not be applied during the fatigue test, yet these loads will contribute significantly to the number of failures during the service life of a fleet of vehicles. The phenomenon was introduced in the discussion of a Rudimentary System in Section 2.4b. On the other hand, there are some situations where the fatigue test will have a probability of failure higher than in the corresponding fleet operation. This can be understood by studying Figure 36. As noted above, there is a discrete load that is encountered once in the average lifetime. Usually, this is the maximum load applied during the test. In this situation, there is a probability of 1.0 of exceeding any load smaller than this maximum test load and a zero probability of exceeding any larger load. The probability of an individual vehicle exceeding this value is less than 1.0 (about .63). These relationships are shown on Figure 36. Thus, the test operation has a higher probability than the fleet operation of exceeding all loads up to the maximum test load. Beyond that point the fleet operation has the higher probability. Which is controlling in determining the total probability depends on the strength distribution. Therefore, it is really not possible to generalize, except to note that the test operation will almost always have a different P_F than the fleet operation. All of these considerations must be recognized in determining the conditional reliability that results from recognition that there may be errors in the fatigue analysis and that successful completion of a particular fatigue test does not necessarily indicate that all of the understrength designs have been eliminated. Figure 37 illustrates the difference between the probability of failure in fleet operation and in a test operation whose spectrum is truncated at the load that will be experienced once during the service life.

The fatigue reliability program described in Volume III makes provision for all of the phenomena just discussed. Basically, it solves Equation (10). It should be clearly understood that the analytical procedure recommended in Section 2.4a for determining the residual strength is not considered to be a panacea for all fatigue problems. However, the concept developed in Reference 12 and its expansion to the Fatigue Damage Index in Volume III of this report have the necessary elements incorporated. Intrinsically, the procedure is solving the correct problem and the answers obtained are qualitatively correct. The point was made in Section 2.3c and reiterated for the fatigue problem in Section 2.4d that errors will occur in any structural analysis. It matters not whether the error is generated by an erroneous mathematical model of the failure process or by an erroneous choice of quantities to represent the particular structure being analyzed. If a set of curves such as those on Figure 35 can be generated, very useful conclusions can be developed from the qualitative relationships. A density function number can be assigned to each condition represented (Example 2 in Volume III presents a four condition problem). These density functions, in effect, represent the likelihood (or probability) that the true P_F curve will fall in the range represented by the analysis for that condition. For instance, it could be assumed that the intended design results are represented by Condition (1) on Figure 35. The results from the design represented by Condition (2) are assumed to stem from an erroneous analysis. In the previous section it was assumed that 75 percent of the structural systems

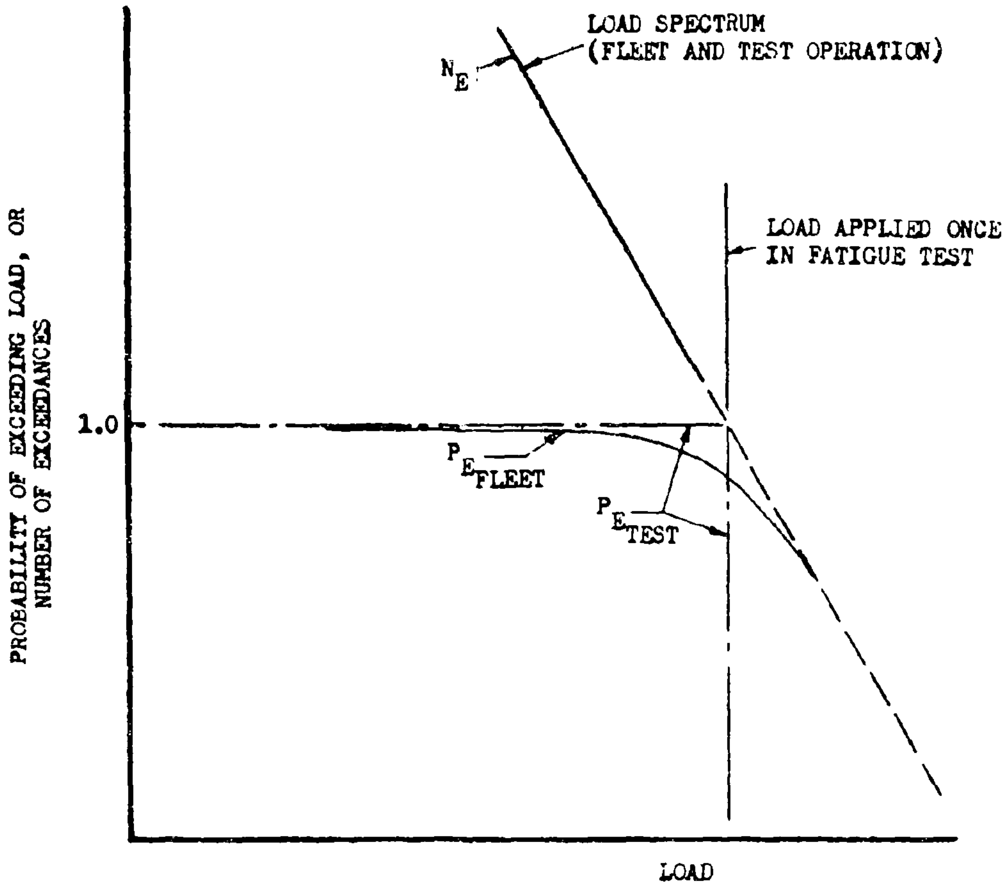


FIGURE 36. FLEET AND TEST LOAD SPECTRA

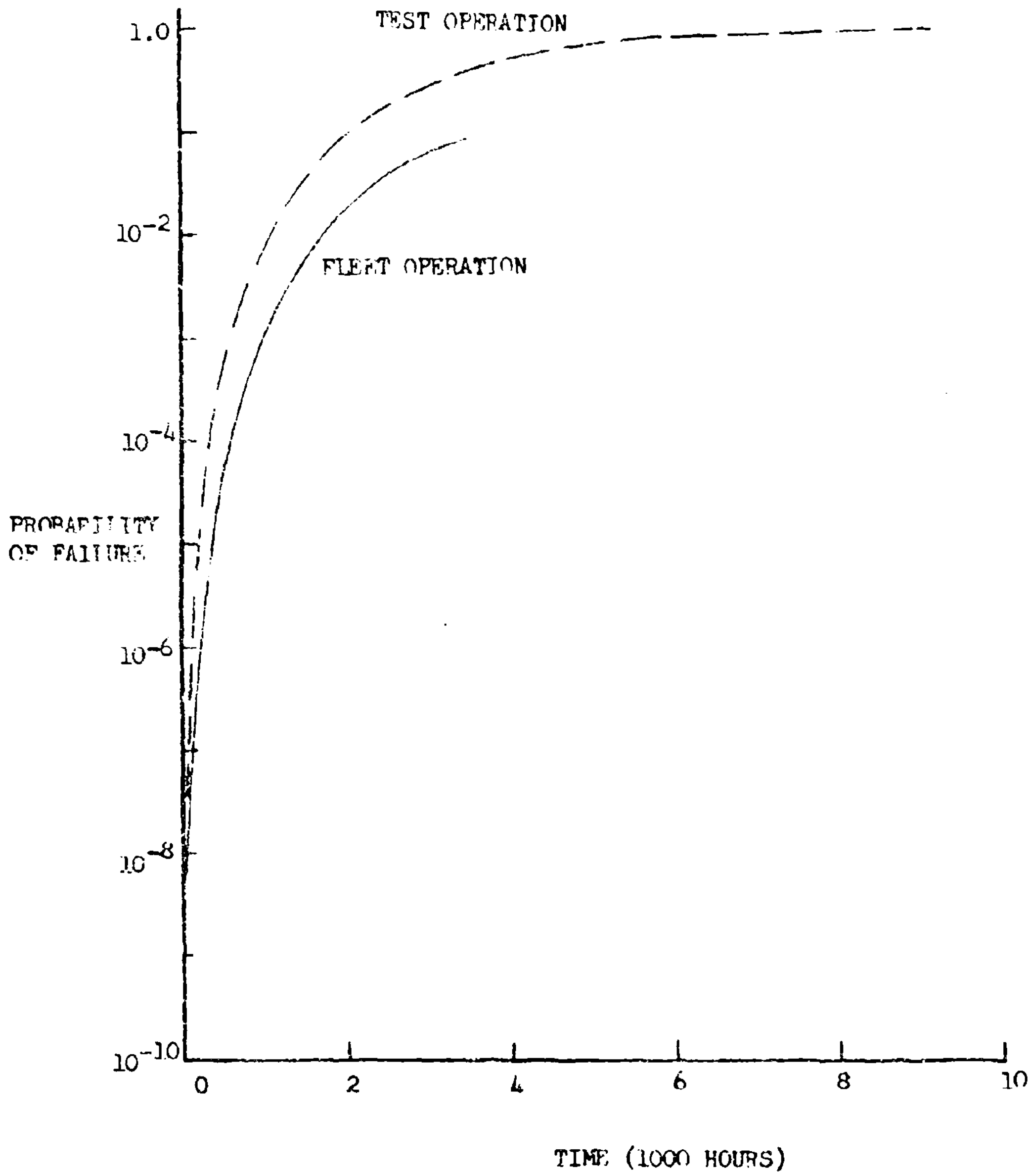


FIGURE 37. COMPARISON OF FLEET OPERATION AND TEST OPERATION

would fall in the Condition (1) category and 25 percent in Condition (2) category. It was shown there that the average failure rate in this situation would be 0.2550 for a 6800 hour life. The comparable value at 3000 hours would be 0.010 actual versus 0.0001 intended. These values are based on systems that go into service without a fatigue test to disclose errors.

Now consider what happens when a fatigue test is conducted. In the 3000 hour c... the P_F for a Condition (2) design in a test to 6000 hours is 0.95. This means that 5 percent of such designs would survive the test to twice the nominal life. The product of the probability of obtaining such a design (0.25) by the probability of passing the test to 6000 hours (0.05) by the probability of failing in service at 3000 hours or sooner (0.040) represents the probability of having a failure from a Condition (2) design. This value is 0.25 x 0.05 x 0.040 = 0.0005. If those structural systems that failed to pass the test are considered to be redesigned to Condition (1) status, the fraction of this class design would be 0.75 + 0.95 x 0.25 = 0.987. The probability of failure of these at 3000 hours would be 0.987 x 0.0001 = 0.0000987. The combined probability of failure of the two sets of designs would be 0.000099 + 0.0005 = 0.000599. Thus, by one fatigue test to twice the operational life, the P_F would be decreased from 0.010 to 0.00069. This is almost the P_F of 0.0001 that would be obtained in a no error situation. The corresponding S.R.'s would be from 0.99 for no tests to 0.9994 for one test with 0.9999 being the theoretical no error value. This simple case illustrates the source of the great improvements in structural reliability.

One of the great virtues of this approach is that it is not too sensitive to the unprovable assumptions. For instance, if the 25-75 ratio were reversed to 75-25, the final S.R. would only drop from 0.9994 to 0.9984. The test would still fulfill its function of disclosing errors and upgrading the final S.R. of the system.

The purpose of the fatigue test is to disclose errors with a high degree of certainty. In Section 2.3d(3) it was pointed out that conducting two or more strength tests of the same design would increase the certainty of disclosing understrength designs. The same principle is applicable in fatigue testing. As an example, the improvement in the S.R. can be determined for the previous case when two fatigue tests are run. The probability of a service failure for a Condition (2) design becomes 0.25 x $(0.05)^2$ x 0.040 = 0.000025. The probability for a Condition (1) design is 0.9993 x 0.0001 = 0.00009993. The combined probability of failure of the two sets of designs becomes 0.0001155. Thus, the S.R. has increased from 0.99 for zero tests to 0.9994 for one test to 0.99988 for two tests. This value has almost reached the 0.9999 predicted if no error is considered in the analysis.

Another technique for increasing the certainty of error disclosure is to conduct a static strength test after completion of the fatigue test. This procedure would reveal those designs where the residual strength is down significantly but not enough to cause a failure under the maximum load applied during the fatigue test. The RS distribution after the completion of the fatigue test would have the form defined by Figure 34. The static test load can

be compared to the RS strength from Figure 34. The fraction of structures with a RS less than the test load could be determined for any particular test life. For the simple example it was determined, using the Volume III computer program, that the probability of failure during application of a test load corresponding to the usual ultimate load would be 0.997 at 6000 hours for a design corresponding to Condition (2) on Figure 35. Then, the probability of surviving a 6000-hour fatigue test, the static strength test, and failing at the 3000-hour service life becomes 0.25 x 0.05 x 0.003 x 0.040 = 0.0000015. The probability of a Condition (1) type of structure failing at the 3000-hour service life is (1.0 - 0.0125 x 0.003) x 0.0001 = 0.000099996. The combined probability of failure of the two sets of designs becomes 0.000101. In this hypothetical case the reliability after the combined fatigue and static test would be virtually identical with the predicted value, despite the substantial possibility of an error in the analysis.

The fatigue situation is very analogous to that depicted on Figures 9 and 10, but with the abscissa in terms of hours of life rather than load. In the example presented earlier, it was assumed that 25 percent of the designs (Condition 2) would fail prematurely compared to the intended life. These designs would be the equivalent of the B, D, E, K, Q, S, and T systems on Figure 9. The 75 percent (Condition 1) whose life is as predicted would correspond to Systems A, C, F, H, J, M, and O on Figure 9. After completion of the fatigue tests, the situation would look more like that on Figure 10. In the discussion on page 83 it was noted that 5 percent of the 25 percent of the Condition (2) designs would pass the test to 6000 hours and be accepted for operations. Those systems that would be understrength operationally after passing the specified test would be equivalent to System Q on Figure 10. The structural reliability in the fatigue situation as well as statically depends on the certainty with which the System Q's will be rejected during the testing procedure and then redesigned to provide the desired strength.

The conditional reliability resulting from various combinations of test life, number of independent fatigue tests, and fatigue tests followed by static tests can be determined by the Volume III computer program. The results are shown on Figures 38 and 39. From parametric studies of this type, deterministic requirements for fatigue testing could be established. For instance, if the SR goal is 0.999, a design would be acceptable if the test article survives to a test life 3.7 times the specified service life. If two articles are tested independently, the test life could be reduced to 2.2 times the service life and for four test articles the test life would only need to be 1.5 times the service life. If a static test to ultimate load follows the fatigue test, the required test life would be reduced to 1.2 times service life.

An analysis of the conditional SR resulting from fatigue tests to a specified multiple of the service life comparable to Figures 38 and 39 can become the basis for fatigue design criteria. A table listing the testing options available to the designer could be added to the present criteria (Reference 15) for each class of vehicle. As an alternative, the test life required for a given SR goal could be established for an individual design using the computer program of Volume III.

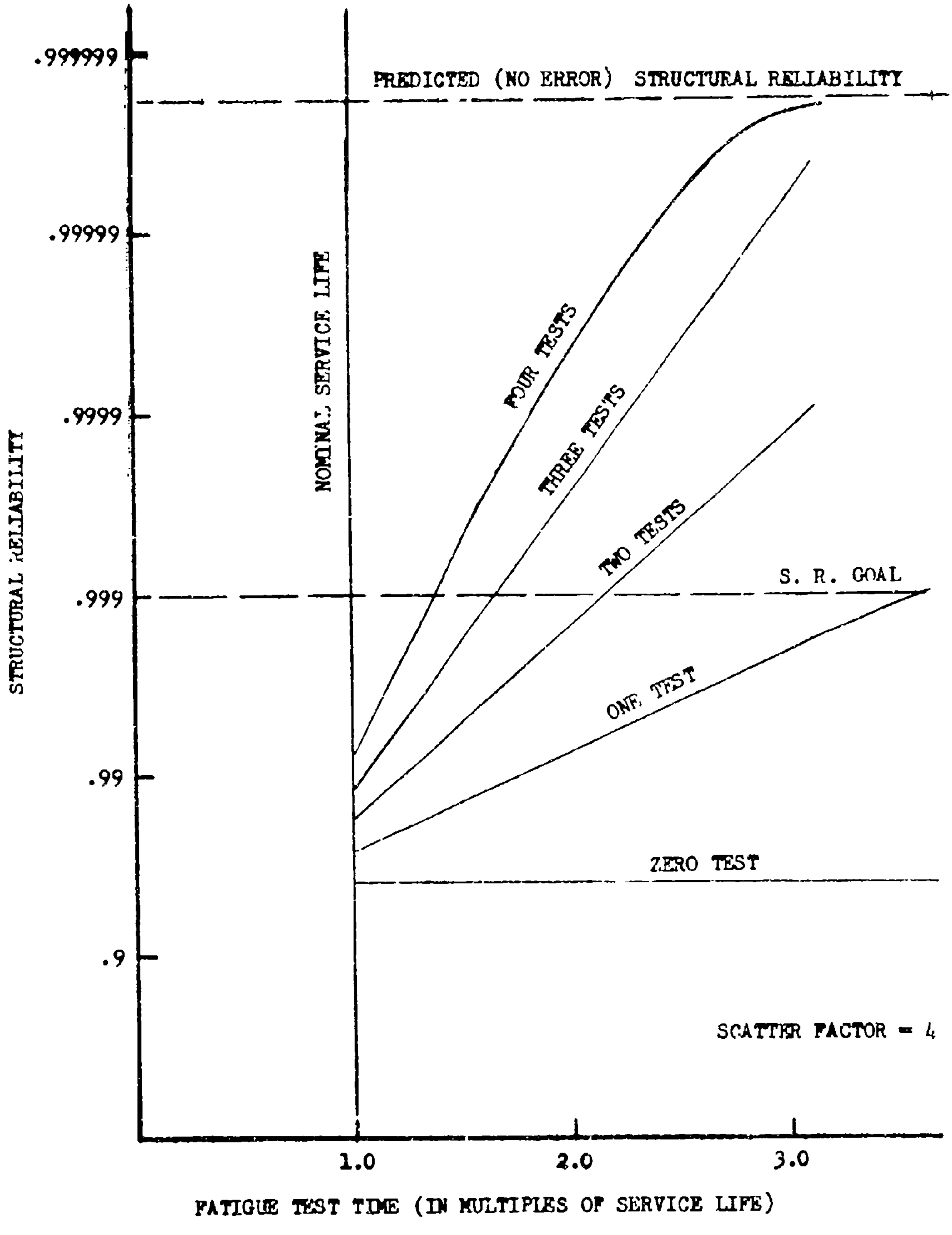


FIGURE 38. EFFECT OF MULTIPLE FATIGUE TESTS

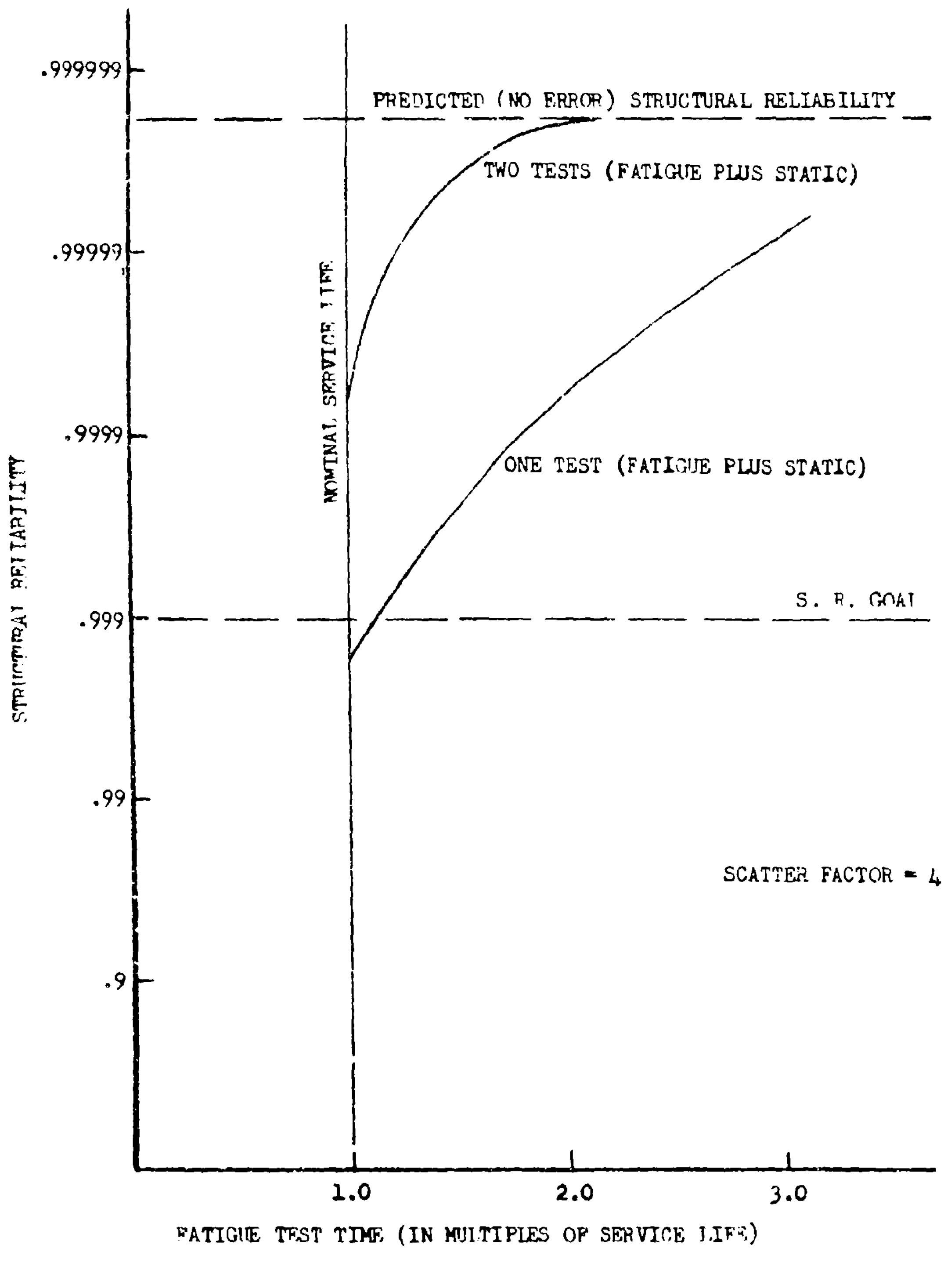


FIGURE 39. EFFECT OF FATIGUE PLUS STATIC TESTING

f. Disclosure of Error in Fatigue Loads and Conditions

The previous section discusses how to develop the SR of a structural system, conditional on the load spectrum being as predicted. Sections 2.3e and 2.3f discussed the problems of disclosing errors in loads and in the choice of design conditions. The same transfer functions govern the determination of the loads for fatigue analysis as for the limit and omega loads for the static design. Therefore, the loads testing performed for static loads should be applicable to disclosing errors affecting the fatigue spectrum. The same reasoning applies to the choice of design conditions. Limit and omega conditions were orginally chosen on the basis of a predicted loading spectrum. Rejection or acceptance of this spectrum is discussed in Section 2.3f. If the spectrum is acceptable for the static design conditions, it should be equally acceptable for fatigue conditions.

g. Proof of Compliance

The proof of compliance procedure for "proving" that a structural system meets the requirements for structural reliability is directly comparable to that discussed in Section 2.3g for static conditions. The basic design is qualified and approved by successful completion of a fatigue test (or tests) to a specified multiple of the service life. The required duration of the test is determined as discussed in Section 2.4e. This test life becomes the deterministic requirement that converts the structural reliability goal into an administrable requirement as discussed in Section 2.3a(2). As the previous discussion in this Section 2.4 makes evident, the choice of the test life requirement relative to the service life is based on statistical considerations. In the same manner that the static test will not reject absolutely all the deficient designs (the System Q's will be accepted), so the fatigue test will not reject deficient designs with absolute certainty. However, those that are accepted will be sufficiently rare relative to the desired SR goal so that such situations will be effectively negligible. Therefore, any system that survives the specified test can be accepted for operational usage with assurance that its structural integrity will be at the desired level even though the SR of individual designs may be somewhat higher or lower than the SR goal established for that class of vehicle. To reiterate, compliance with a specified structural reliability number can never be proved; compliance with a specified fatigue test life is a simple go, no-go proposition.

SECTION III

TECHNICAL APPROACH

3.1 GENERAL

The philosophy or rationale guiding the development of the proposed new procedure for structural design criteria is described in the previous section. Specific details of how to apply that philosophy to the design of structural systems are described in this section.

3.2 CRITERIA FORMAT

a. Structural Reliability Goal

The definition of the structural reliability goal is the starting point of the new procedure. It must be emphasized that the quantity defined is a goal, not a requirement. In Volume I, it is pointed out that there is no procedure for accurately determining the actual structural reliability of a particular structural design, so a structural reliability number cannot be used as a specification requirement. However, establishing a structural reliability goal is necessary to establish the reliability level that controls all subsequent requirements.

A structural reliability goal should be chosen for each vehicle system. At present, it is suggested that these structural reliability goals be established by class of vehicle. For instance, the structural reliability goals presented on Table I of this report could be added to Table I of MIL-A-8861.[16] Typical structural reliability goals would be 0.99 for fighter class aircraft, 0.9999 for liaison aircraft, and 0.999999 for transports. Alternatively, a share of the total vehicle reliability could be allocated as the structural reliability goal.

Step 1. Decide on a structural reliability goal consistent with the vehicle mission. Document the decision in the vehicle specification.

b. Expected Operational Usage

In order to establish limit and omega design conditions which have a probability of exceedance in accordance with those suggested on Table I, it is necessary to define the expected operational usage. This definition should take the form of a curve of the probability of exceeding the parameter in question. Figure 2 is typical of the curves needed to define operational usage. Where insufficient statistical data are available, this step can be omitted and the limit and omega conditions established as noted in the next section. Figure 49 illustrates the fact that predicted operational usage is derived from statistics of comparable operations in the past, from an analysis of the operational capabilities of the new vehicle, and from pure judgement. The prediction of the operational usage is validated and updated at several

places in the design and deployment cycle of the vehicle. First, there should be a specific agreement by the personnel responsible for the non-structural system concerned with the particular parameter. In general, the agreement will be based on the same type of data used by the structural organization to make the initial prediction. However, the concurrence will help to ensure that the prediction is realistic relative to the operational considerations. Since most of the parameters defining the design conditions are controllable in the operation of the vehicle, the process of obtaining concurrence from the non-structural system will serve to alert those concerned to the expected operation so that there should be a tendency to operate the vehicle in a manner consistent with the prediction. The final validation of the prediction can only come from comparing actual operations of the vehicle with the predictions. The feed-back of this information to the initial prediction is shown on Figure 49 and is noted as Step 9.

Step 2. Predict the operational usage of the vehicle in the form of a curve of the probability of exceeding various magnitudes of a particular parameter.

c. Design Conditions

If the expected operational usage has been properly determined in the previous step, the choice of design conditions is almost automatic. Table I defines the relationship between the probability of exceeding limit and ultimate conditions and the structural reliability goal. If the probability function is available from Step 2, the limit condition is chosen as that condition whose probability of exceedance is equal to the appropriate value from Table I. The omega condition is chosen in the same fashion.

If, for any reason, the statistical function cannot be predicted, limit and omega conditions can be established on a judgement basis. Whether determined from the statistical function or on a judgement basis, the qualitative meaning of the limit condition is that it represents the upper bound of the normal or expected operational condition. Therefore, if those responsible for the structural system and those responsible for the non-structural system can agree that a particular condition is necessary for normal operation of the vehicle but that more severe conditions are not necessary, then that condition by decree is a limit condition. By this agreement, the structural system is committed to "never" failing at limit. The non-structural system is committed to operating "most" of the time at less than the limit condition.

The omega condition can be established on the same kind of judgement basis as the limit condition if statistical data are not available. However chosen, if it is agreed for the structural and non-structural systems that the omega condition is an extreme condition reached only in abnormal operational situations and beyond which no structural capability is needed, the omega condition is established by the agreement. In most cases, the approach to omega conditions can be controlled by observing the prohibition against exceeding the limit condition. The structural system accepts the responsibility for assuring that most of the individual structures will survive the omega condition, but with absolutely no need for capability

to survive beyond the omega condition.

Step 3. Establish the various limit and omega conditions which define the performance requirements for the structural system and operational limitations for the non-structural systems.

d. Design Loads for Limit Conditions

The structural loads associated with each limit condition are calculated by the same procedures that would be used in the Present System. These limit loads are then multiplied by a Limit Test Factor of Safety to obtain design loads. The only difference between the design loads of the new procedure and the ultimate loads of the Present System is that the Limit Test Factor of Safety to be applied to the limit loads is not a fixed number. It is defined by Figures 24 and 25. This factor of safety depends on the structural reliability goal established in Step 1 and the strength scatter, γ_s, of the structure when subjected to the environment associated with each particular limit condition. Thus, the γ_s may vary from one condition to another and from one component of the vehicle to another.

Step 4. Calculate the design loads for the limit conditions by multiplying the limit loads associated with the various limit conditions by the limit factor of safety defined on Figures 24 and 25.

e. Design Loads for Omega Conditions

The design loads for omega conditions are determined in a manner analagous to those for limit conditions. The loads associated with each omega condition are calculated and multiplied by an omega factor of safety. It should be noted that the omega factor of safety is a completely different function than the limit factor of safety. As shown on Figures 12 and 20, the omega factor of safety will be 1.0 for most conventional structures with relatively low strength scatters. In principle, the differences between omega loads and limit loads are no greater than those between two different limit conditions in the Present System. In practice, there may be some difficulties in determining omega loads. One of the obvious differences between limit and omega loads (used in the broad sense discussed in Section 2.3a(3)) is that the temperatures for the omega condition may be higher than those for the corresponding limit condition because the omega velocities and flight attitude may be greater. Because the omega conditions are extreme conditions, non-linearities in aerodynamic loads will be more prevalent. Aeroelastic effects will be larger and in some cases will involve yielding of the structure. The difference in calculating limit and omega loads is one of degree, not one of basic procedure. The strength scatter, γ_s, for the omega condition may be different than the γ_s for the limit condition. This should be considered in determining the omega factor of safety from Figures 12 and 20.

Step 5. Calculate the design loads for the omega conditions by multiplying the omega loads associated with the various omega conditions by the omega factor of safety defined on Figures 12 and 20.

f. Strength Requirement for Structural System

The strength analysis under the new procedure is very comparable to that under the Present System. Margins of safety are calculated using allowables that have the same meaning as they do under the present system. In many cases, particularly where temperature differences are not significant, the allowables at limit and omega conditions will be identical. It will be obvious whether the design loads for the limit or the omega condition are the more critical. In such cases, only the critical condition would need to be considered and the entire procedure becomes equivalent to that in the Present System. In other cases, the allowables for the omega condition may be less than those for the corresponding limit condition but the limit factor of safety may be larger than the omega factor of safety. In such cases, the critical condition may not be obvious and both limit and omega condition will need to be analyzed.

Step 6. Substantiate the strength of the structural system in reports comparable to those required by Paragraph 3.7 of MIL-A-8868.[17] Use allowables from MIL-HDBK-5[18] and comparable sources to calculate margins of safety.

g. Proof of Compliance with Strength Requirements

Strength tests in which the test structure successfully supports the design loads for the limit and omega conditions constitute proof of compliance with the strength requirements. The requirements of the new procedure for testing are comparable to those of the present procedure. There is a sharp line of demarcation between compliance and non-compliance so there can be no question of whether or not the test is successful. The difference between the new procedure and the Present System is the number of tests required. Proof of compliance for both limit and omega conditions is necessary although a single test will satisfy both requirements in most cases. In addition, the Test Factor of Safety may be based on multiple tests to reduce the factor of safety as shown on Figures 20 and 25. If this option has been selected, two or more nominally identical test articles must be fabricated and each must complete the specified test without failure. The proof of compliance for the fatigue situation is comparable to that in the Present System. The differences are that the ratio between test life and nominal service life depends on the fatigue scatter factor, the structural reliability goal, the number of test articles, and whether a static test is conducted after completion of the fatigue test.

Step 7. Prove compliance with the strength requirements by successfully completing static tests for all of the critical limit and omega design loads. Complete fatigue tests to the test life defined on Figures 38 and 39.

h. Validation of Limit and Omega Loads

Procedures to validate the calculation of limit loads are essentially identical with present practice. Operational limitations will usually preclude any flight measurement programs beyond limit conditions. However, much can be accomplished towards verifying the loads (really, disclosing

possible errors) by indirect procedures as discussed in Section 2.3g(2).

Step 8. Validate the limit and omega loads associated with the limit and omega conditions. Measure limit loads directly. Extrapolate measured loads to omega conditions by validating parametric functions to the greatest extent possible by full-scale flight tests and by wind-tunnel tests.

i. Validation of Limit and Omega Conditions

The previous procedures, if properly carried out, ensure that the structure will attain the desired structural goal provided that the probability of exceeding limit and omega conditions is no greater than was predicted when the conditions were selected. Various sources of information such as eight-channel statistical data or a count of the number of times "red-line" values are exceeded can be used to decide if the vehicle is being operated in a manner consistent with the expected probabilities for exceeding limit and omega conditions. Tests such as described in Section 2.3f and 2.3g(3) should be employed to validate the choice of limit and omega design conditions.

Step 9. Validate the limit and omega design conditions by monitoring actual operations and comparing actual operational usage with the predicted values used as the original basis for the design. If the actual usage is greater than acceptable for the design conditions, take steps to modify the operations or to increase the strength, as necessary.

j. Structural Failure Situations

In the event that a failure in the structural system should ever occur, the new procedure would not change present procedures for determining the cause and for taking remedial action. The deterministic nature of the requirements and well-defined lines of demarcation in defining understrength or overload regions will assist in determining a probable cause in any failure investigation. Section 2.3h and Figure 47 indicate some of the decisions that may result from an accident investigation.

Step 10. Decide on a cause of failure and the action to take in case of any structural failure.

SECTION IV

FUNCTIONAL FLOW DIAGRAMS

The visualization of the various functions that contribute to the final decision that the structural system has a satisfactory structural reliability can be aided by functional flow diagrams such as presented in this section of the report. The terminology and format used in these diagrams is discussed in detail in Volume I. Figure 1 in this volume reproduces from Volume I the Generalized Functional Diagram — Structural Design System.

In Figure 1 (and in the various diagrams of Volume I), the portion of the structural design system involving the collection and application of information to make decisions has been designated as the Informetics field. In order to decide that the structural system is satisfactory, it is necessary to determine the results actually being achieved in terms that may be directly compared with corresponding data that represent desired results. In Volume I, following the concepts introduced by Draper in Reference 1, the comparison is made from data generated in a Desired State Information System (DSIS) and an Actual State Information System (ASIS). It was noted in Section 2.2 that these functions are phrased in the language used by Draper[1] but that this language was just a formalism for what is really common sense.

The basic elements of the Informetics section of the Proposed Structural Design System are presented on Figure 40. This figure shows that the Desired State is established from the vehicle mission through choice of a structural reliability goal to the definition of limit and omega conditions that are consistent with the S.R. goal. Then, the Desired State is divided into two parts. First, the strength of the structural system should be consistent with the defined limit and omega conditions. Second, the operations of the vehicle must be consistent with the defined limit and omega conditions. If the Desired State represented by these two functions, strength and operations, is achieved, the S.R. goal will be achieved. The limit and omega conditions are discrete conditions that can be defined numerically. The meaning of the term "consistent with defined limit and omega conditions" can be quantitized as discussed in Section II. Also, it is outlined in more detail in subsequent figures in this section. Therefore, it is possible to determine the Actual State and compare it with the Desired State.

The determination of the Actual State of the strength of the structural system is determined in three phases, as it has always been. First, the strength is determined analytically; then, it is verified by strength test; and, finally, operational results furnish some additional information on the strength of the system. There are two sources of information on the Actual State of operational usage. These are (1) analytical predictions before operations begin, and (2) data from monitoring the actual operations in various ways such as by simply noting in log books when a red-line is exceeded or by elaborate eight-channel recording programs.

When this information on the Actual State is compared with that for the Desired State, management decisions can be made that operations with the vehicle and the strength of the vehicle are consistent with the limit and omega conditions. From these two decisions follow the decision that the structural system has a satisfactory S.R. level for the vehicle as operated. If the decision is negative, the decision can lead to corrective action to improve the situation.

The chain of decisions leading from definition of the new vehicle concept to the final decision that the S.R. level is satisfactory is presented as a Structural Reliability Decision Network in Figures 41 through 48. The need for each of these decisions is discussed to some degree in Section II. With this discussion as background it appears that Figures 41 through 48 are self-explanatory. Each of these decision boxes represents a contributing factor to the final decision on Figure 48 and the corresponding decision on Figure 40. These individual decisions are supported by the appropriate Actual State/Desired State Information System. These supporting ASIS/DSIS represent detail portions of the corresponding systems on Figure 40. The supporting ASIS/DSIS systems for some (but not all) of the decision boxes on Figures 41 through 48 are presented on Figures 49 through 55. The decision made is indicated by the double lines on the appropriate boxes. The small numbers on the lower lefthand corner of these boxes are identical with the number on the corresponding box in the Decision Network (Figures 41 - 48). These diagrams also correspond to similar diagrams in Volume I. The meaning of the individual boxes is discussed in detail in Section II of this report.

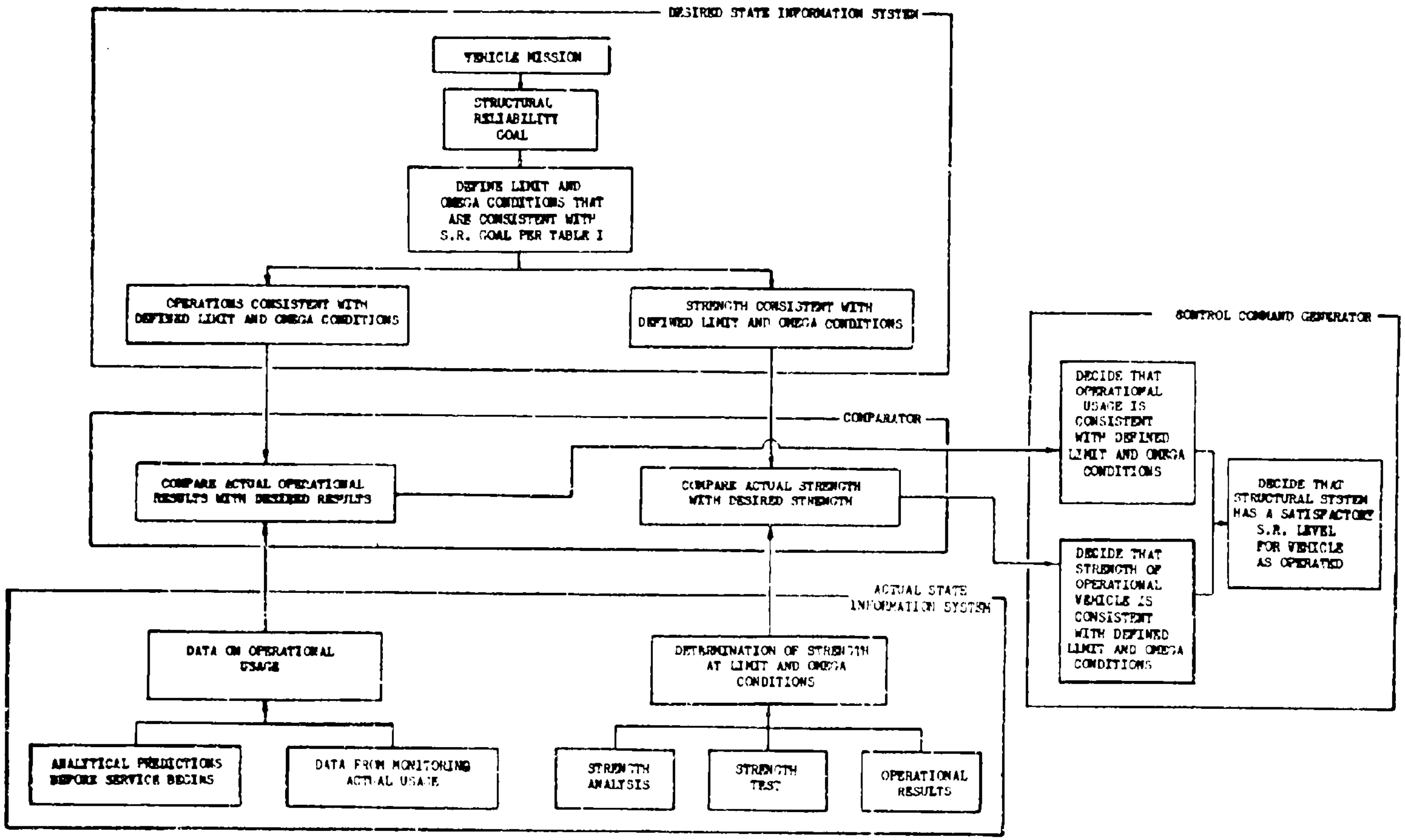


FIGURE 40. INFORMETICS SECTIONS - PROPOSED STRUCTURAL DESIGN SYSTEM

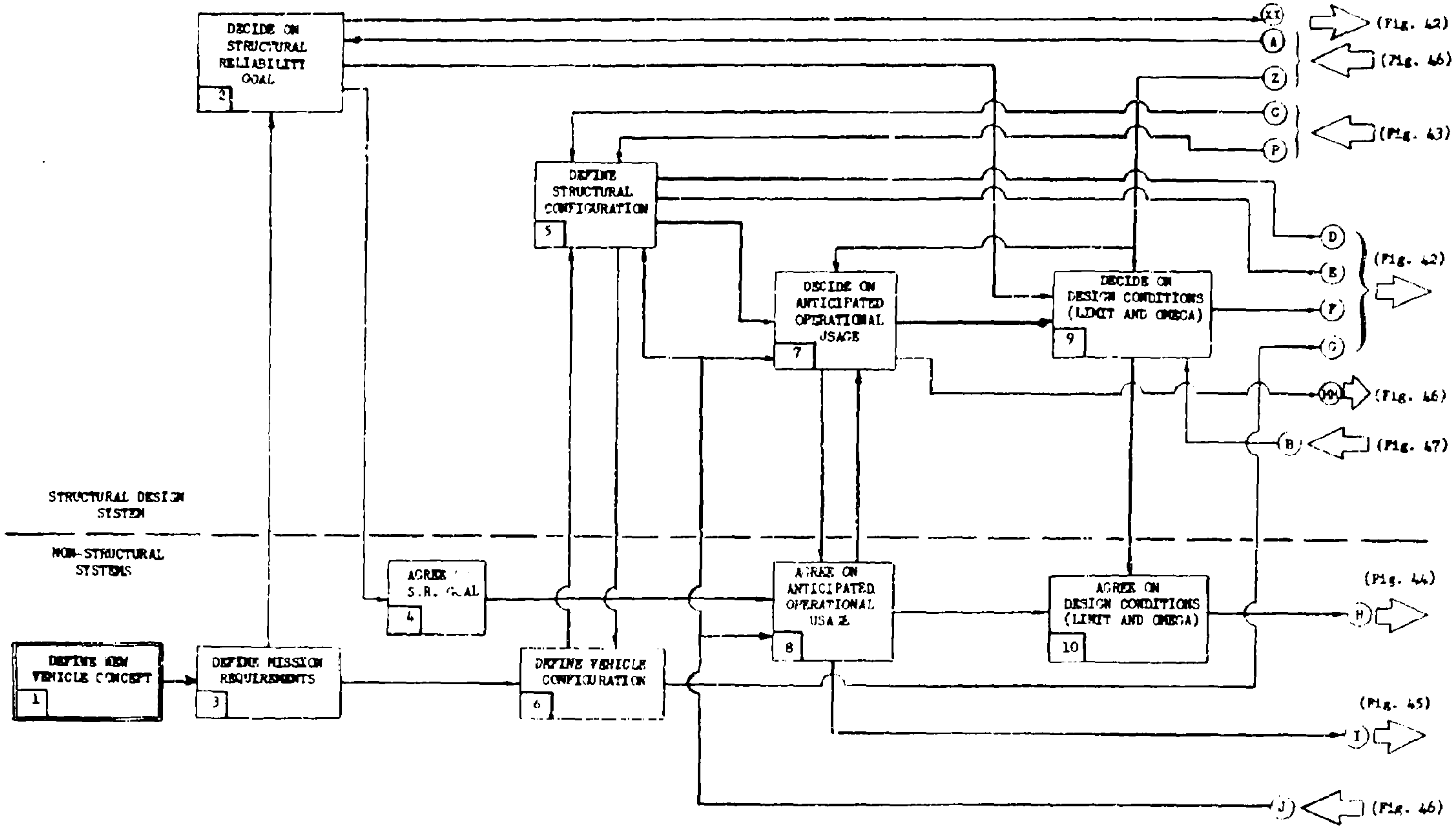


FIGURE 41. STRUCTURAL RELIABILITY DECISION NETWORK (DESIGN CONDITIONS)

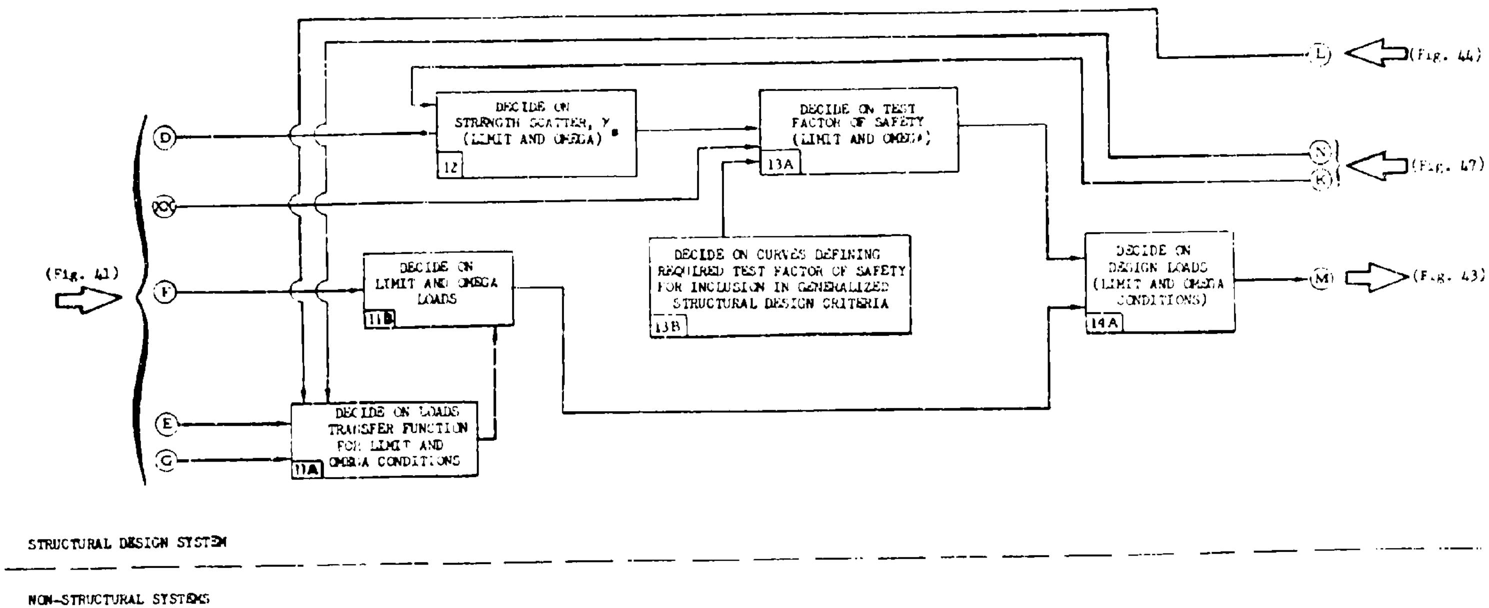


FIGURE 42. STRUCTURAL RELIABILITY DECISION NETWORK (DESIGN LOADS)

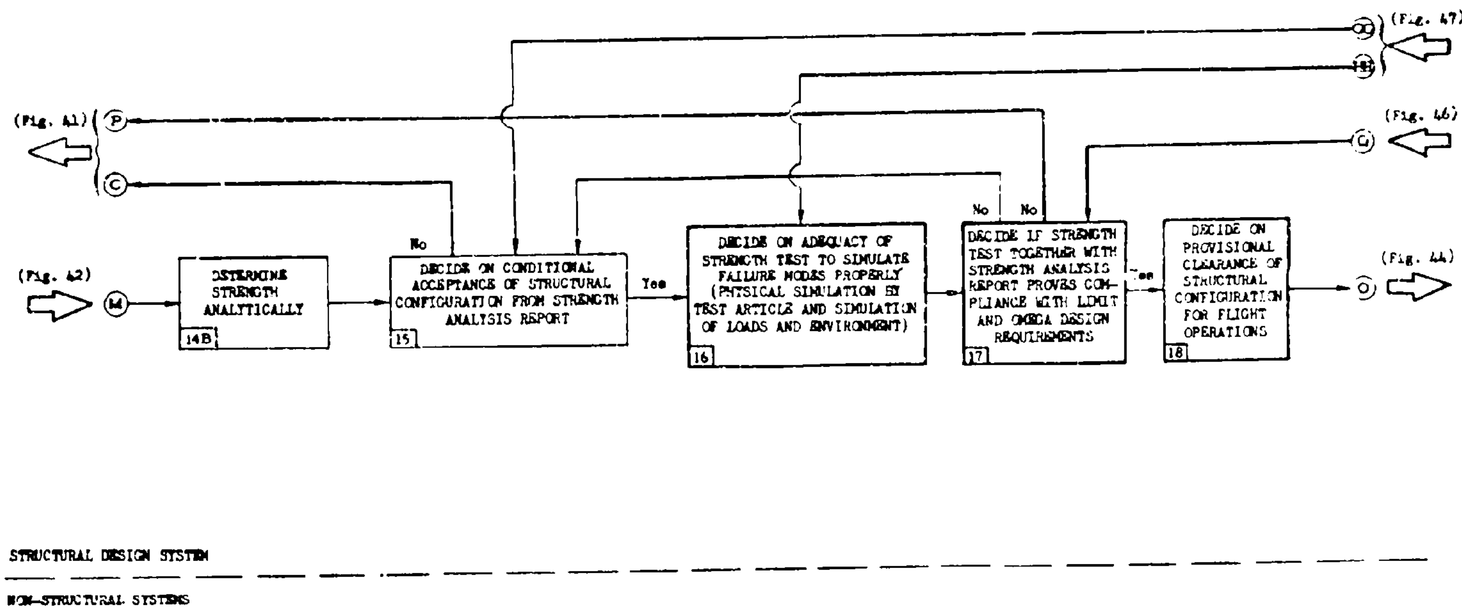


FIGURE 43. STRUCTURAL RELIABILITY DECISION NETWORK (PROOF OF STRENGTH)

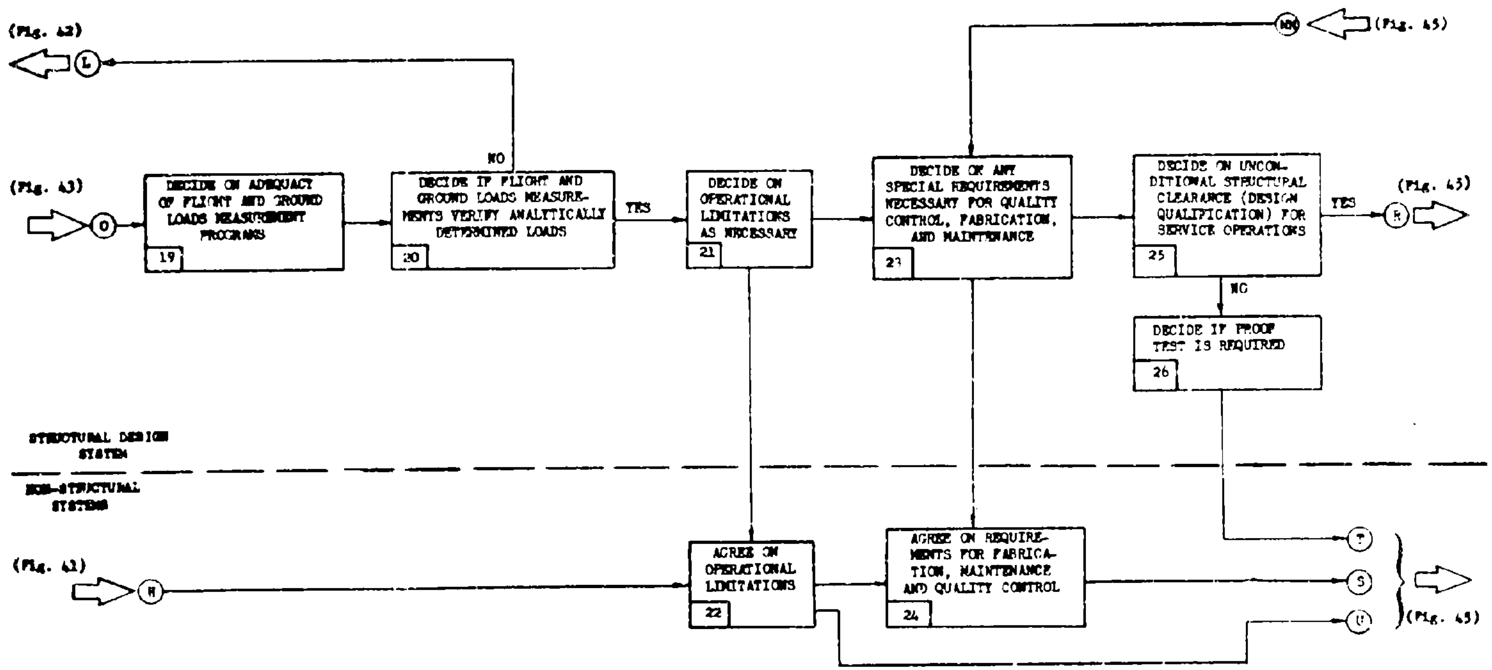


FIGURE 44. STRUCTURAL RELIABILITY DECISION NETWORK (DESIGN QUALIFICATION)

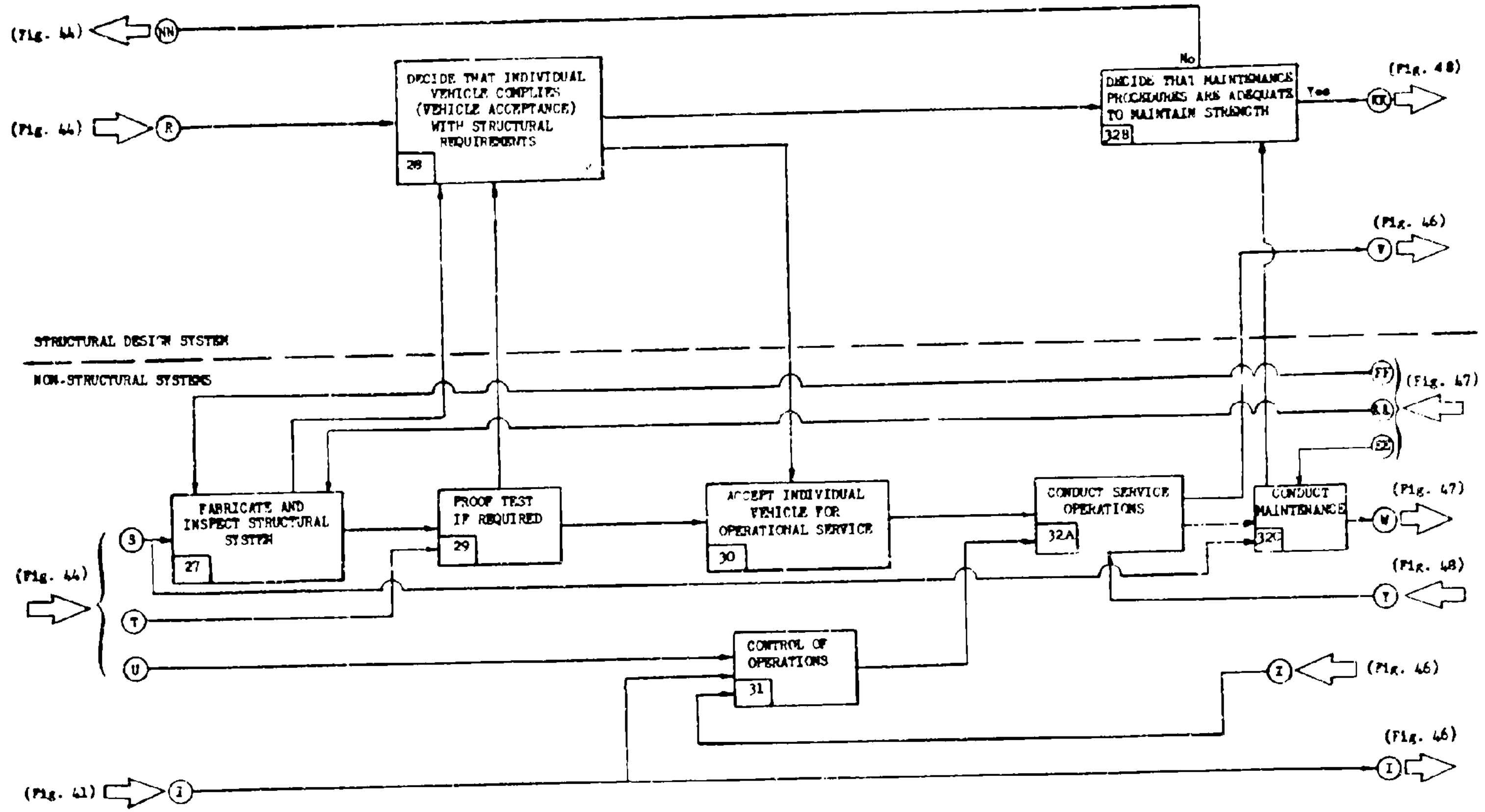


FIGURE 45. STRUCTURAL RELIABILITY DECISION NETWORK (VEHICLE PRODUCTION AND OPERATION)

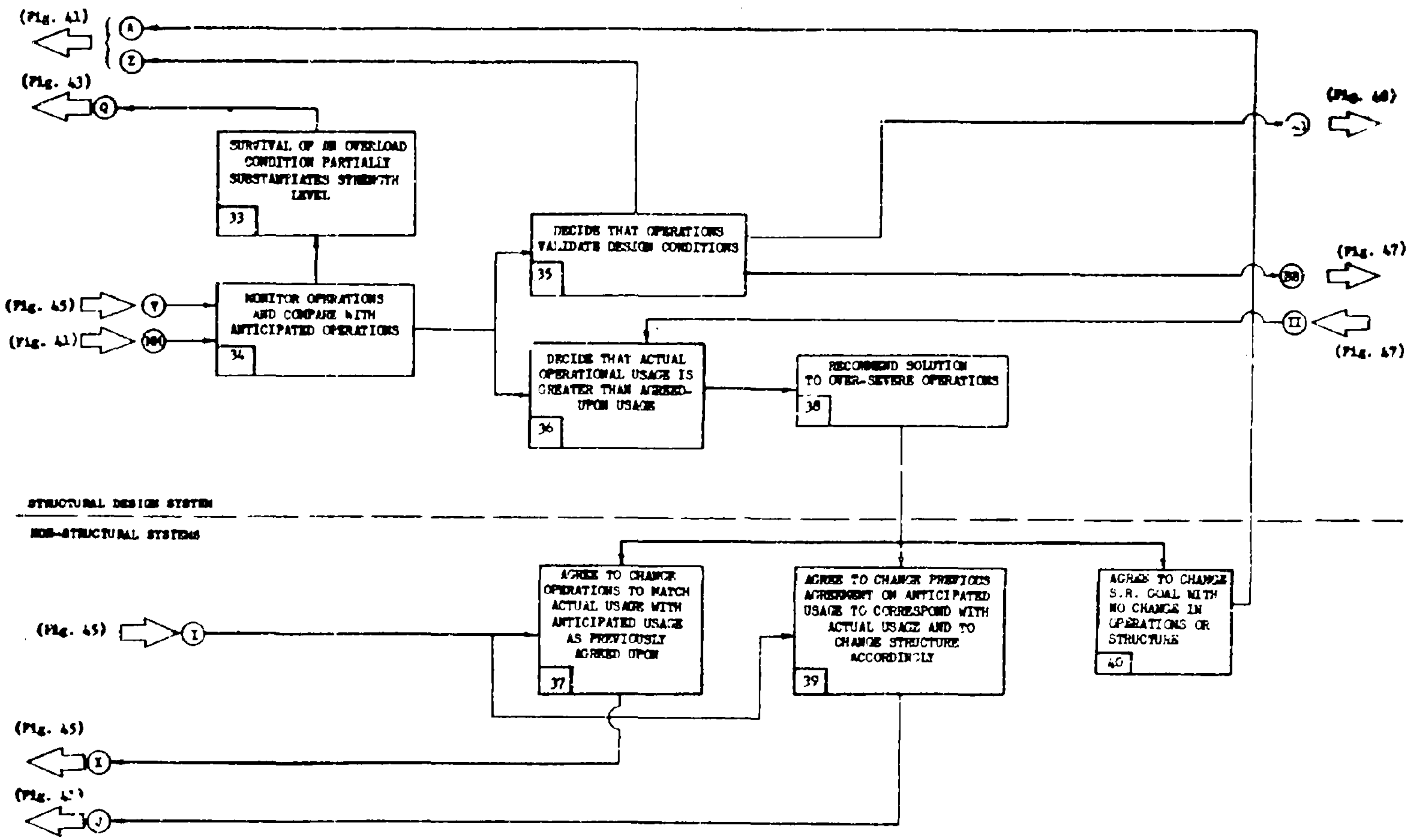


FIGURE 46. STRUCTURAL RELIABILITY DECISION NETWORK (VALIDATION OF OPERATIONAL USAGE)

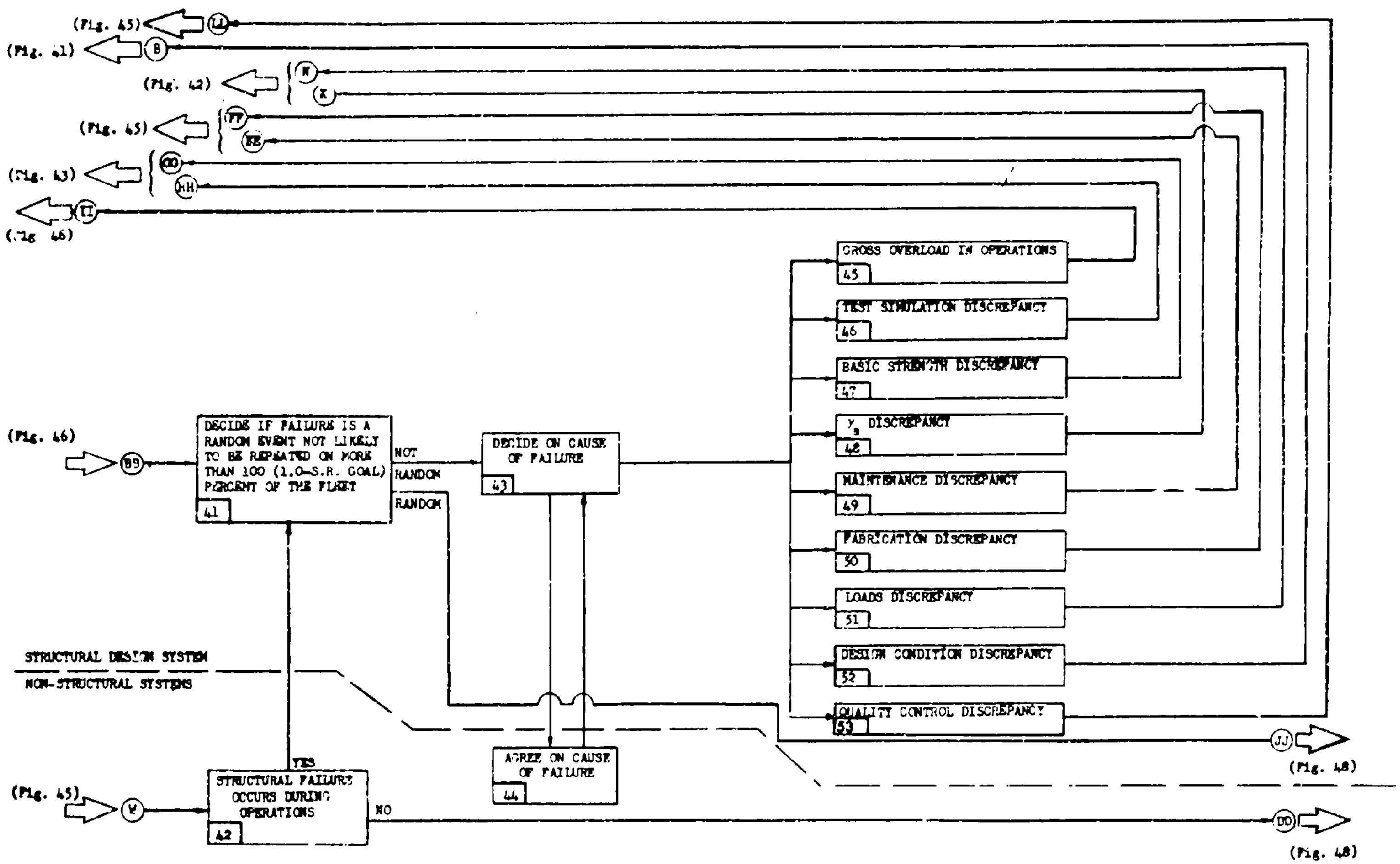


FIGURE 47. STRUCTURAL RELIABILITY DECISION NETWORK (OPERATIONAL FAILURES)

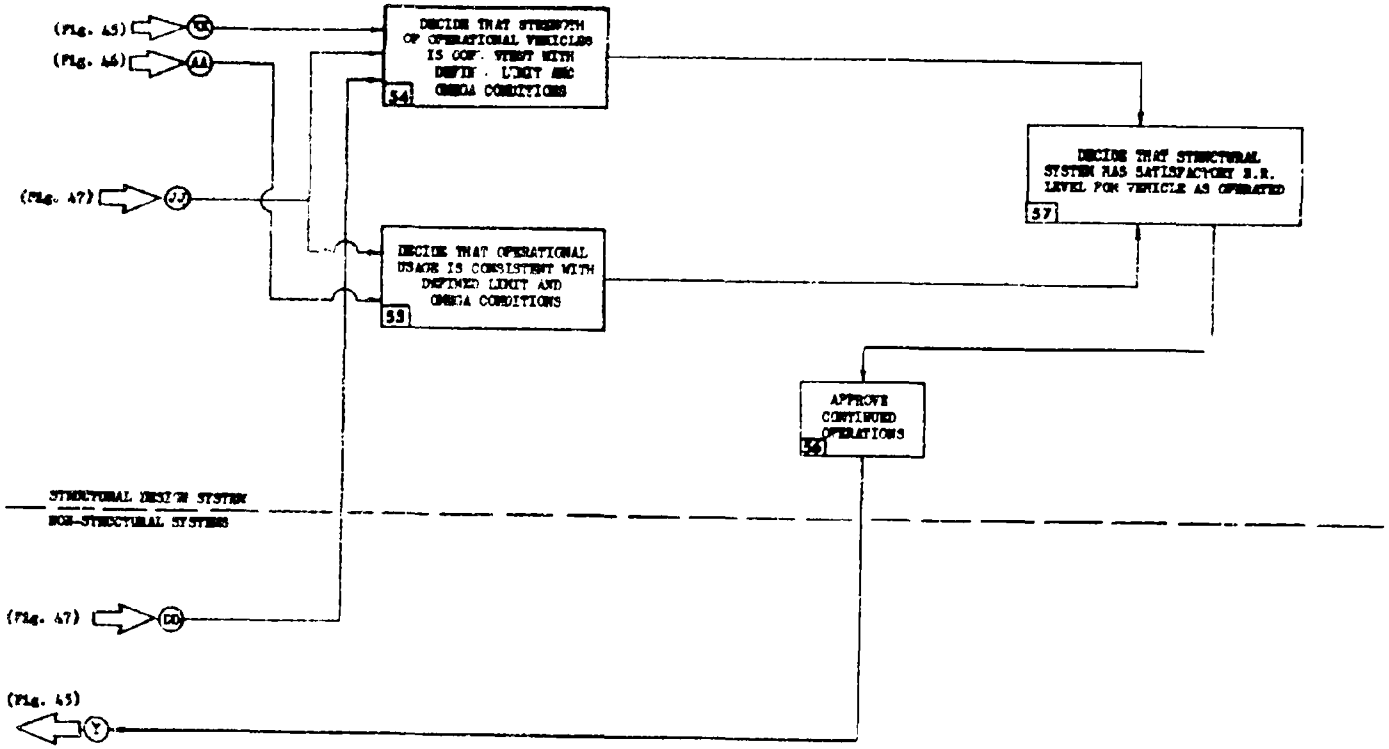


FIGURE 48. STRUCTURAL RELIABILITY DECISION NETWORK (SATISFACTORY STRUCTURAL SYSTEM)

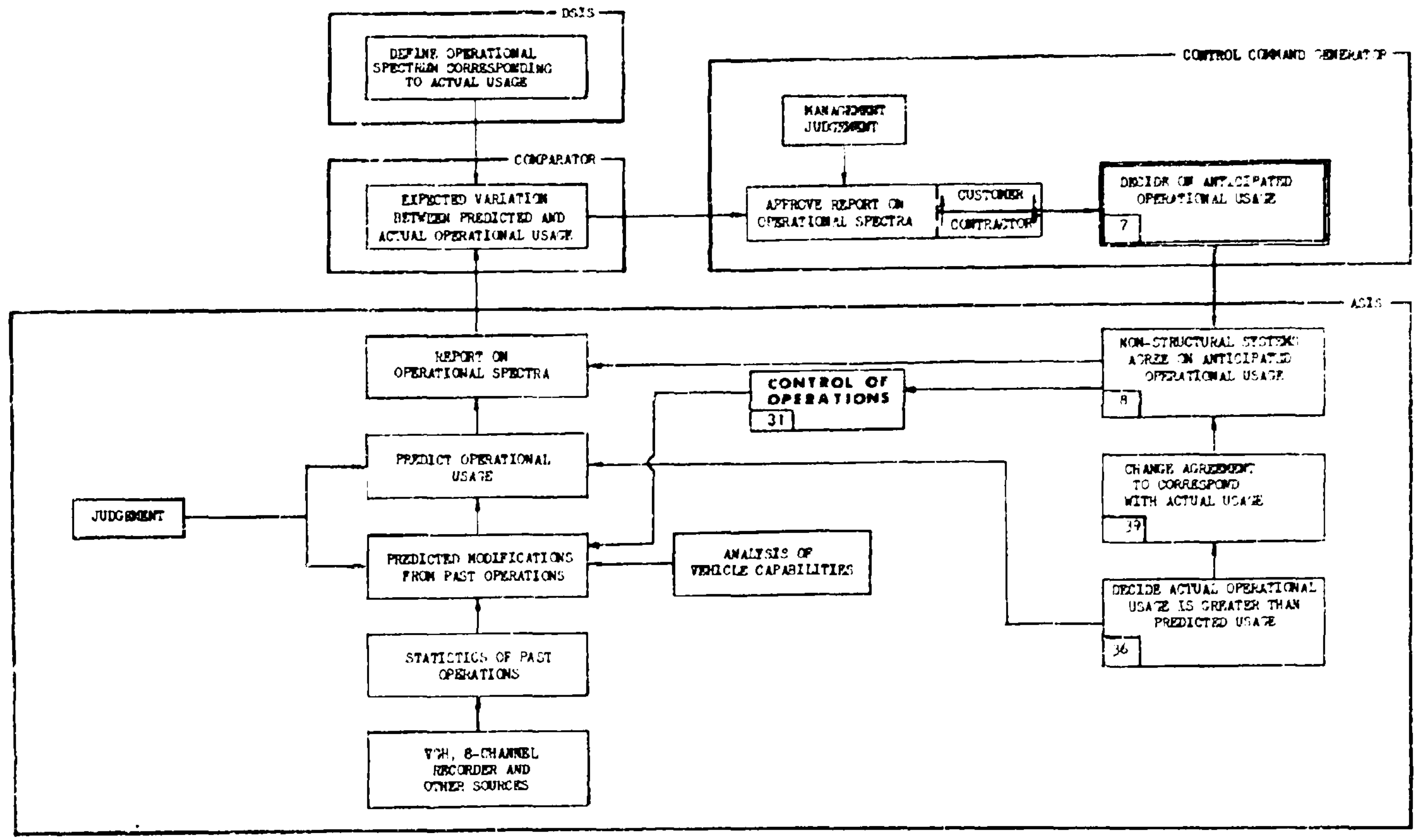


FIGURE 49. ASIS/DSIS USAGE DECISION

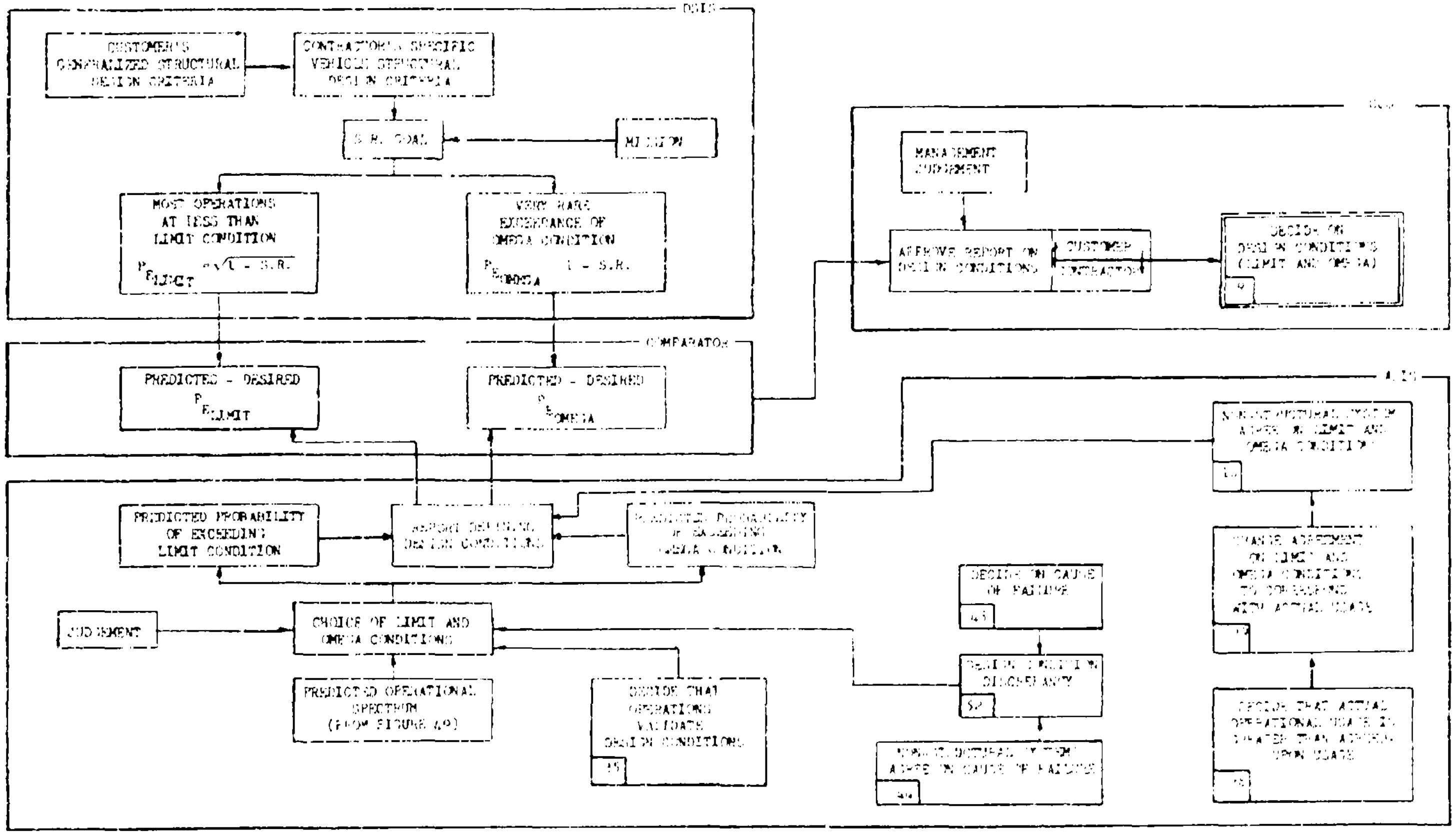


FIGURE 50. ASIS/DSIS CONDITIONS DECISION

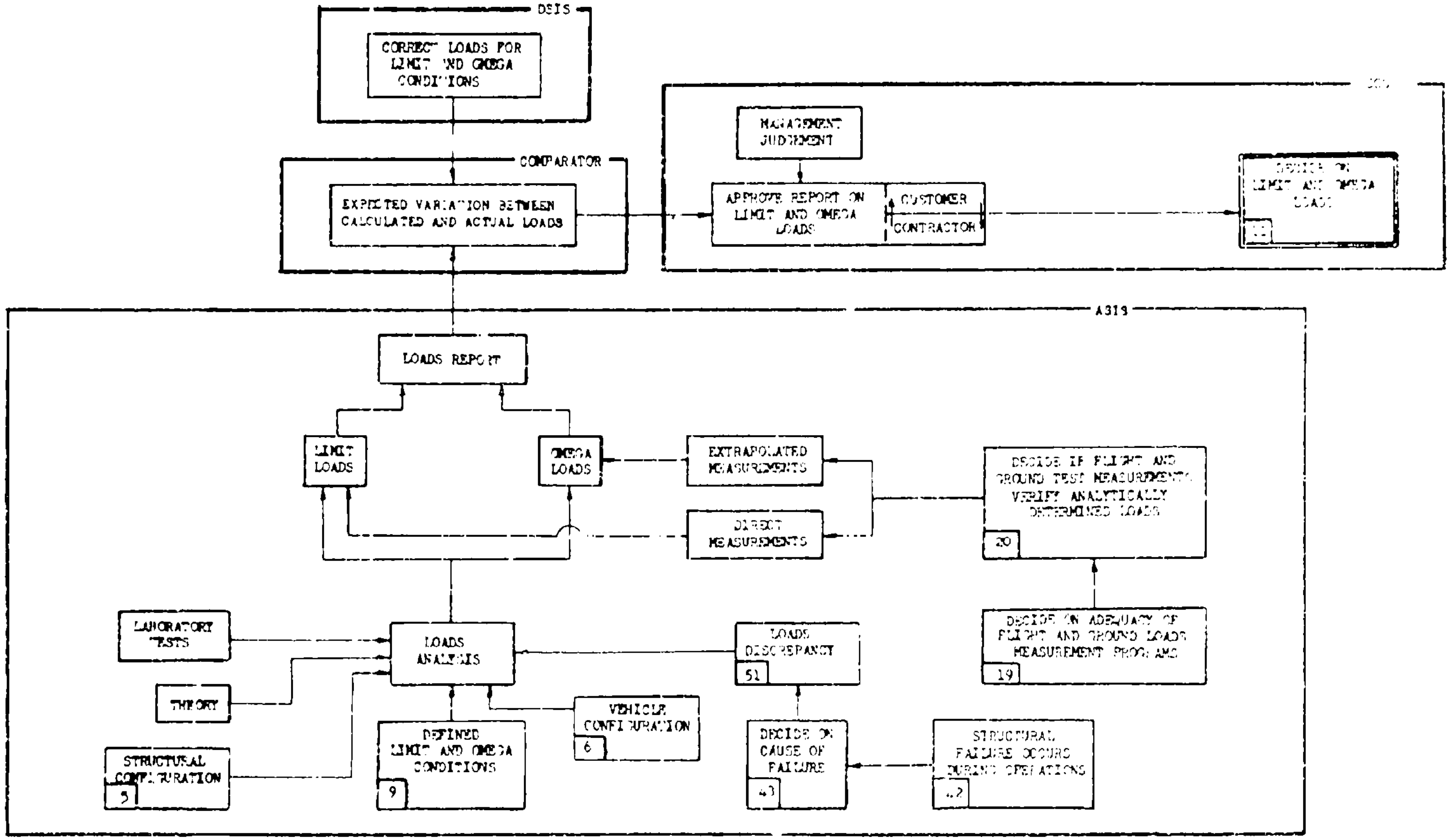


FIGURE 51. ASIS/DSIS LOADS DECISION

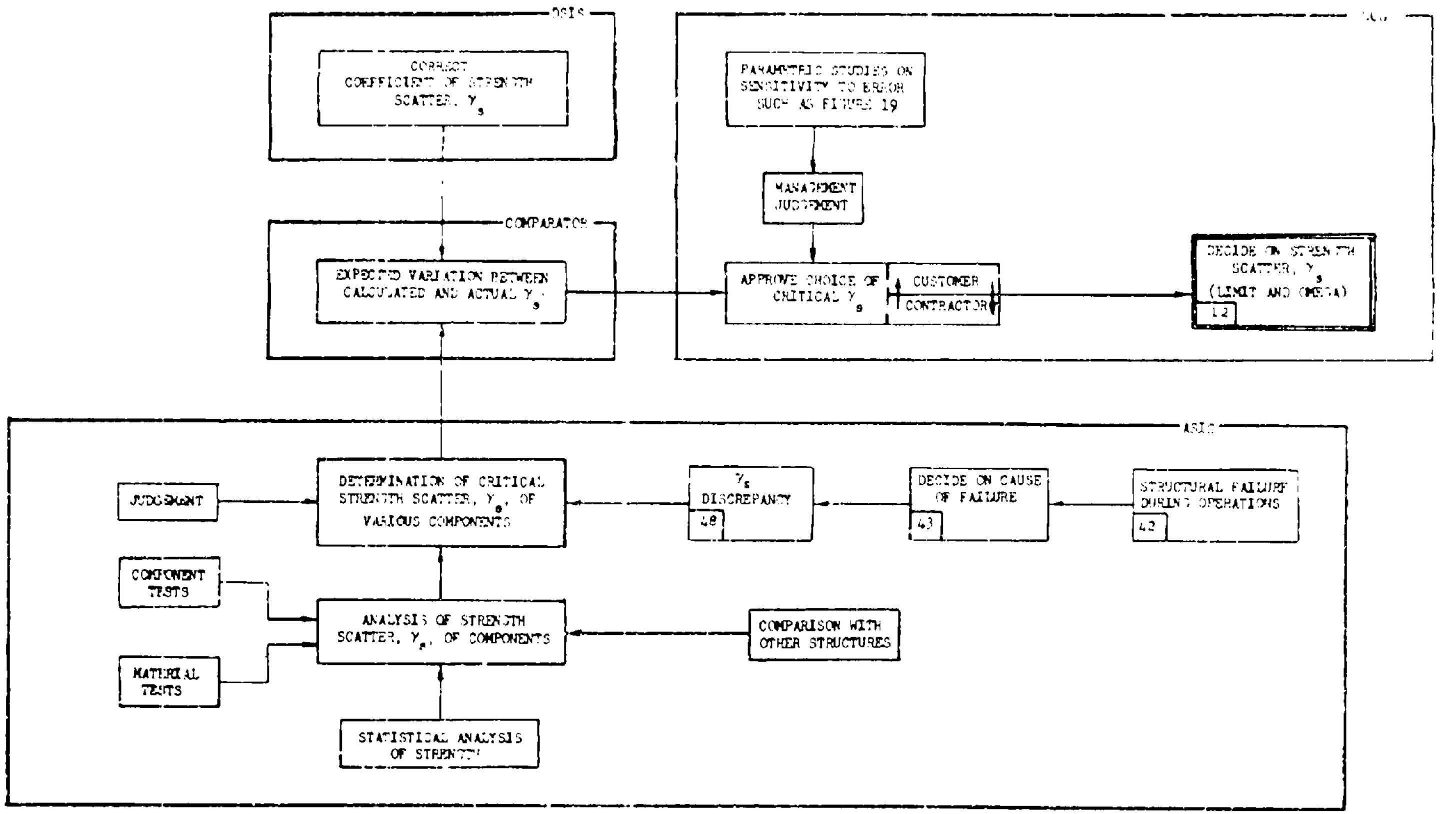


FIGURE 52. ASIS/DSIS STRENGTH SCATTER DECISION

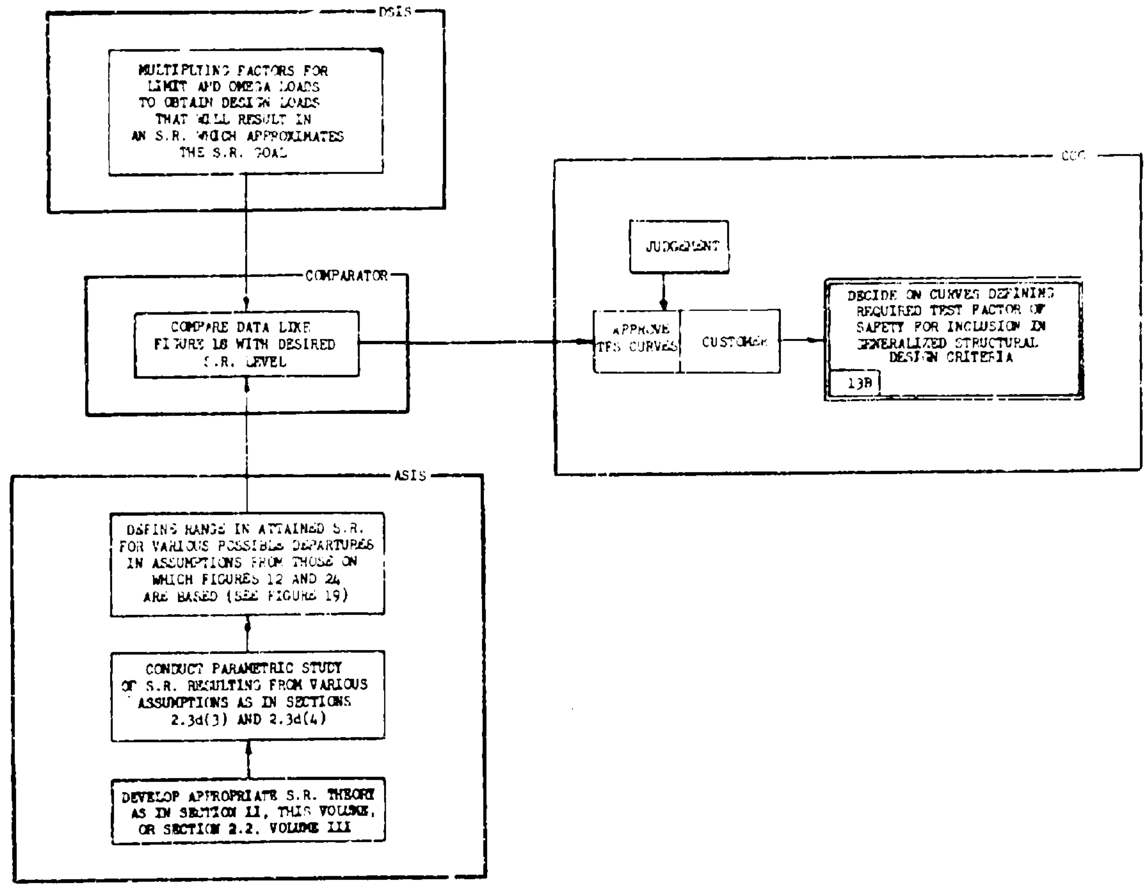


FIGURE 53. ASIS/DSIS TEST FACTOR OF SAFETY

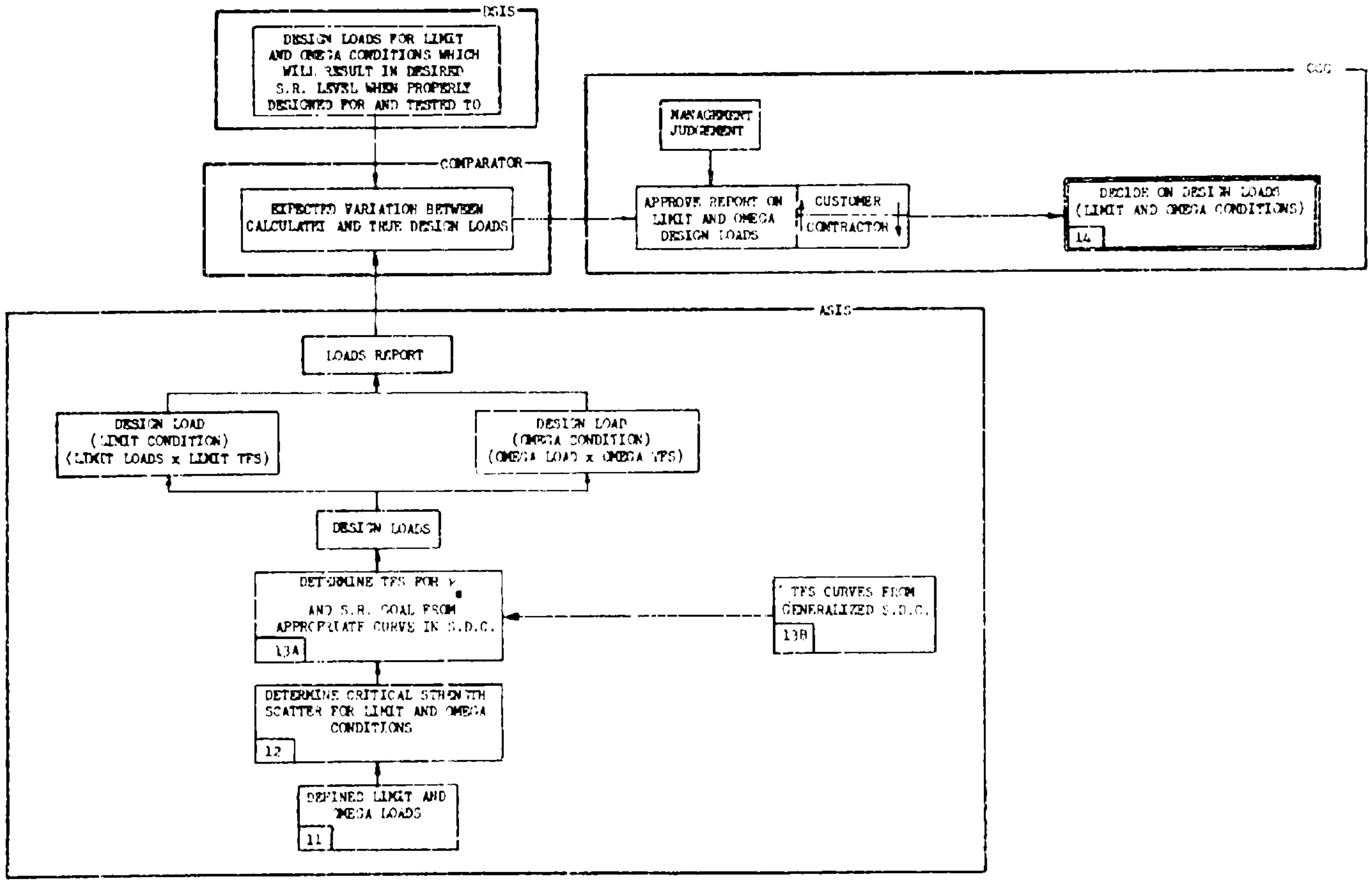


FIGURE 54. ASIS/DSIS DESIGN LOADS DECISION

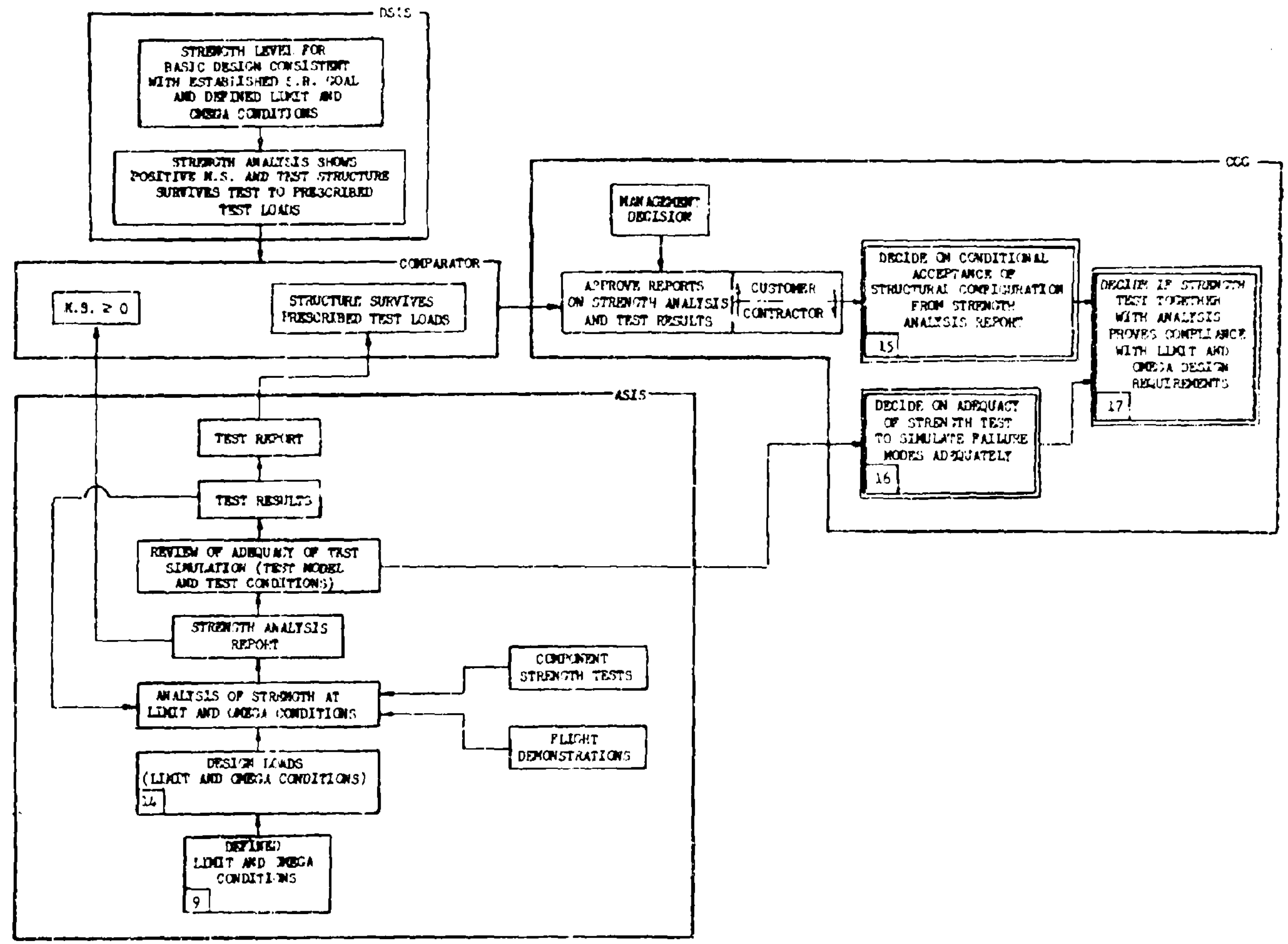


FIGURE 55. ASIS/DSIS STRENGTH COMPLIANCE DECISION

SECTION V

SYNOPSIS OF NEW PROCEDURE

5.1 GENERAL

The new procedure, developed in the study documented in the three volumes of this report, defines the requirements for quantitative structural criteria based on statistical considerations. Because of the necessity to thoroughly justify and explain the new procedure, the documentation is quite lengthy. It is recognized that there are many who will not be able to study the complete development of the new procedure but who desire to understand the essence of the new procedure. The synopsis presented in this section is designed to satisfy that need. The entire procedure is summarized in seven steps at the end of this section.

First of all, the proposed new procedure represents a modification of the Present (Factor of Safety) Structural Design System, not a completely different approach. The form of the procedure is unchanged although the numbers and the meaning of the numbers may differ. Structural designers and analysts do not need to unlearn their present methods and learn new ways for designing structural systems. It is considered to represent a desirable characteristic when experienced engineers comment, "But this procedure is really not much different from what we've always done."

The new procedure allows — in fact, requires — consideration of the statistical distribution of those parameters that truly affect structural integrity (quantitized as structural reliability). However, all of the statistical manipulations are performed at the beginning of the analytical procedure. The statistical operations are used to make decisions that define deterministic values for design conditions and for factors applied to the loads associated with these deterministic conditions. The loads analyst, the strength analyst, the structural designer, and the structural test engineer will be working with discrete conditions, discrete loads and discrete strength allowables just as they always have.

5.2 BASIC CONCEPT

The basic concept of the new procedure is that the structural system should have the structural capability to survive designated overload and understrength situations. The Present (Factor of Safety) Structural Design System provides such capability through application of a factor of safety to the limit loads to determine design ultimate loads. However, it provides this capability indirectly and inconsistently. It is noted in Section 2.2 that one vehicle with a 1.5 factor of safety might be able to attain 1.75 times the limit operational condition while another vehicle with the same factor of safety might attain only 1.25 times the limit operational condition. Also, it is pointed out in Section 2.3d(4) that structures with a large scatter in strength will fail largely due to understrength rather than from overload.

As a result of such considerations, the proposed new procedure departs from the Present System by establishing explicit requirements for understrength and overload situations. These requirements are separate and distinct and are based on probabilities and statistics so as to be consistent with a level of structural reliability appropriate to the vehicle mission. An illustration of the separate provisions for understrength and overload situations is presented in Figure 56. The central bar of Figure 56 indicates that the limit design load includes a provision to handle structures that are understrength so "no failure" will occur at the limit load. This requirement is discussed in detail in Sections 2.3a(1) and 2.3d(4). The right or the left bar indicates the overload provision discussed in Sections 2.3a(1) and 2.3d(3). The left bar illustrates the situation when a relatively large overload provision is necessary so that this requirement is more critical than the understrength provision. The right bar shows the situation when the overload provision is relatively small. In this case the understrength provision is more critical and governs the design. Once the appropriate design values are chosen, they are as deterministic and as easy to administer as the corresponding values in the present system.

5.3 DETAIL PROCEDURE

a. Structural Capability Requirements

The starting point of the procedure is to adopt a structural reliability (S.R.) goal. It is expected that these goals would be established for various classes of vehicles as suggested on Table I. Thus, a fighter aircraft might have an S.R. goal of 0.99; a bomber, 0.9999; and a transport, 0.999999. However, more or different S.R. goals might be established. It is quite feasible to choose the S.R. goal so as to be consistent with the reliability of other vehicle subsystems, if this action is appropriate.

From the S.R. goal, two numbers are derived representing the probability of exceeding an operational limit condition and the probability of exceeding an operational omega condition. Suggested values for these two probabilities are given on Table I. The definition and meaning of the omega condition will be taken up later. A limit condition in the new procedure represents essentially the same thing that it does in the Present System. This means that a limit condition is the upper bound of the normal or expected operational conditions. The statistical definition of the frequency of exceeding a limit condition is an extension to the Present System. However, it is not intended that the new procedure will change the numerical values of limit conditions significantly from those specified in the Present System. Furthermore, if there are insufficient statistical data available to make a good prediction of the probability of exceeding the limit condition, the limit condition can be chosen on a judgement basis. Since the design limit condition serves as the basis for operational limitations, it should be just high enough so that most normal operations can be conducted without exceeding the limit condition.

In effect, the statistical calculations, on which the choice of a limit condition is based, are a prediction of the expected results in future operations from a knowledge of past results. Even if it is necessary to base the choice of a limit condition on a judgement decision, the decision is

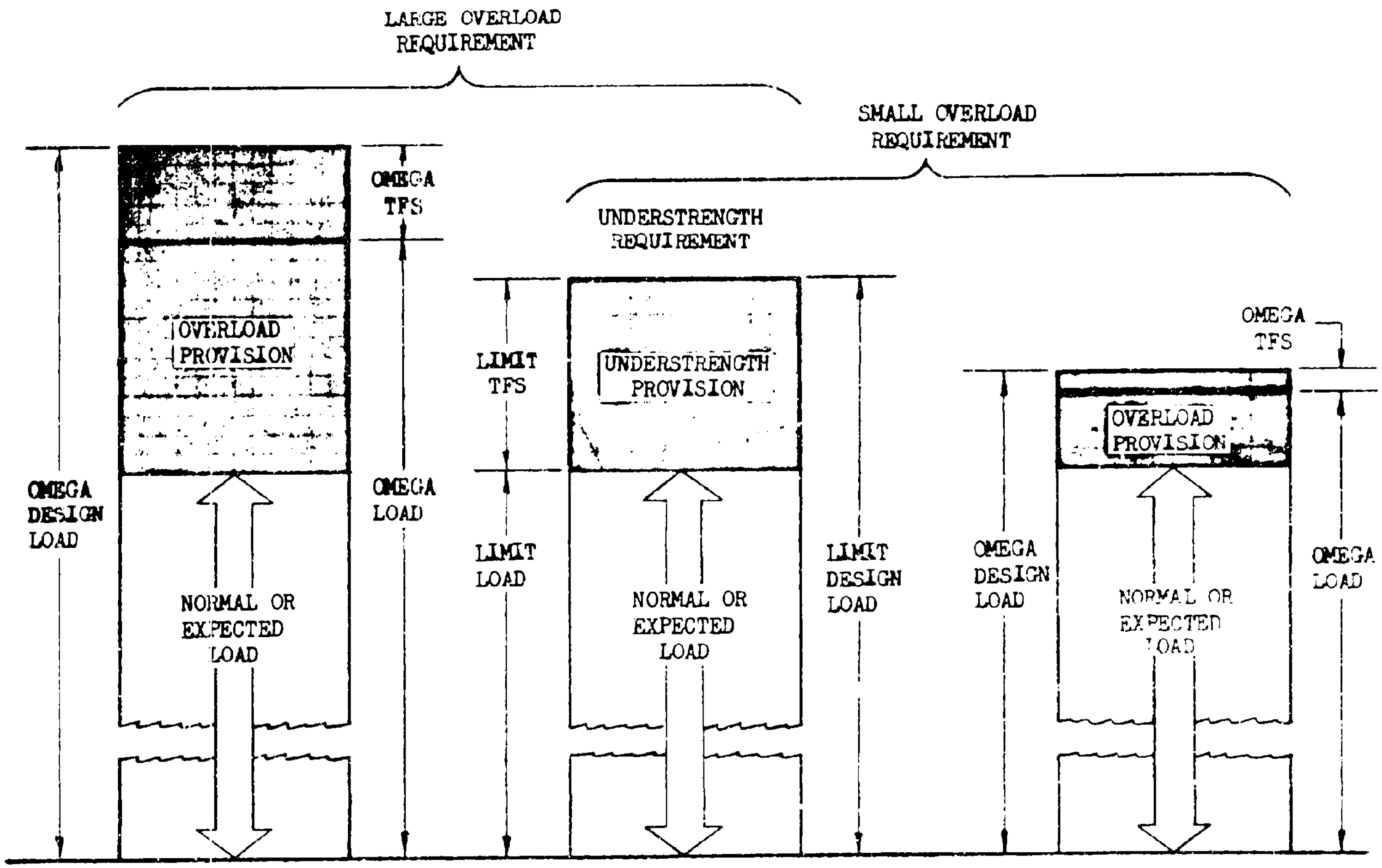


FIGURE 56. OVERLOAD AND UNDERSTRENGTH REQUIREMENTS

still a prediction of future results. The only difference is that the judgement prediction is less sophisticated than the statistical prediction. The final structural reliability of a vehicle is rather insensitive to the actual probability of exceeding limit condition so the choice is not too critical.

The definition of a limit condition is the first step in establishing the performance requirements for a structural system. Since a limit condition, by definition, is a normal or expected condition and is established as a permissible condition by the operating limitations, structural failure is not acceptable at limit condition or less. But, even if perfect S.R. up to limit conditions were attained so that no structural failure ever occurred below limit condition, it would not be enough to insure that the structural reliability goal would be reached. Most structural failures occur as a result of overloading the structure beyond the established limit conditions. Therefore, some requirement for structural capability beyond limit condition and some control of the frequency of encountering an overload condition must be established if a structural reliability goal is to be met.

This need to establish the overload capability of the structural system is the basis for introducing the concept of an omega condition to the new procedure. To illustrate this need, suppose that the structures in a fleet of vehicles were designed to just barely survive an operational condition substantially above the limit condition. But suppose that this overload condition occurred on one out of every ten vehicles. Then, the structural reliability of the fleet could not be higher than 0.9 even if none of the failures occurred below the limit condition. Conversely, if an operational condition can be defined whose probability of exceedance is the complement of the desired structural reliability, the S.R. goal will be attained if the structural system can always survive this condition. It is axiomatic that a one-in-a-million level of reliability (S.R. = 0.999999) cannot be obtained if the structure cannot survive a condition that occurs on more than one-in-a-million vehicles. Therefore, the definition of such a condition is a necessary step in defining a structural system that will meet a desired S.R. goal. Any operational condition that has a probability of being exceeded which is equal to the complement of the desired S.R. goal is designated as an omega condition.

The initial choice of limit and omega conditions is based on statistical considerations governed by the desired S.R. However, once the choice is made the two conditions become completely deterministic. Whether or not the limit and omega conditions truly satisfy the statistical expectations that led to their choice is not germane. These conditions explicitly define the interface between structural performance requirements and operational constraints. This interface is deliberately placed at the operational condition, such as load factor, velocity and weight, which can be measured and controlled during flight and ground operations. Once stated, the limit and omega conditions become independent and divorced from their origin. They represent the structural capability that should be provided by the structural system. They also define the level of operational usage that must not be exceeded if the desired S.R. is to be attained. The numbers defining the limit and omega conditions represent definable, administrable performance requirements for the structural system. The significance of these requirements can be described in qualitative terms to develop an appreciation of the intent behind the definition. Then, a quantitative definition of the requirements will follow.

The limit condition is an expected and permissible operational condition so the structural system should never fail at limit. The limit condition is the upper bound of normal operations so exceedance of the limit condition should not occur unless something is abnormal in the vehicle operation. For those conditions that are controllable by man or by other subsystems, exceedance of a limit condition represents a violation of an operational limitation.

The omega condition is not an expected operational condition and it usually represents a gross violation of the operational limitation. Most of the structural systems should survive the omega condition but there is no requirement for any structural capability beyond the omega condition. Consequently, if there is any vehicle operation at or beyond the omega condition failure may be expected to occur. This definition of a finite upper bound on the required structural capability is an important characteristic of the new procedure. It avoids the difficulty inherent in a Purely Statistical Structural Reliability System where the structural capability needed to provide a given S.R. cannot be predetermined since it depends on how the vehicle is operated. In the new procedure responsibility for preventing structural failures beyond the omega condition by avoiding such operations is explicitly transferred to other non-structural systems.

The preceding discussion is intended to make crystal clear the fact that the reliability of a structural system depends on considerations beyond the purview of those responsible for the structural system. Structural reliability is not something intrinsic in the structural system. The S.R. achieved by a given system may be high if operated one way and very low if operated in a more severe manner. Achieving structural reliability depends on two separate and distinct considerations. First, the structural system obviously must be at the strength level defined by the specified structural performance requirements. Second, and not so obvious, the interface with non-structural systems must be explicitly defined and operations must be so controlled that they do not exceed the overload capability of the structural system.

The structural performance requirements previously defined as no failure at limit condition and most, if not all, structures surviving the omega condition must be qualified slightly before the requirements can become the basis of a realistic procedure. "No" failure at limit must be redefined to "very rare" failure at limit. "Very rare" is quantitized by a probability of failure goal at limit condition which is related to the total probability of failure that will be tolerated. If the probability of failure at limit is no more than one percent of the total P_F as suggested in Table I, such a value can be considered to be rare in the context of the tolerable number of failures. This one percent goal serves as the basis for determining the design and test requirements for limit conditions in the new procedure.

b. Structural Strength Requirements

If the strength distribution were known precisely, the relationship between the limit condition loads and the strength allowable (usually the 99-percent-exceed value) needed to provide a given S.R. could be determined by standard statistical procedures. However, the strength distribution cannot be assumed to be known. Reference 6 documents the fact that structures fail during strength tests relatively frequently at levels substantially below the

values expected on the basis of a strength analysis. Figure 9 shows a typical distribution of the strengths resulting in a group of different structural systems from analysis alone. Figure 5 indicates that, if future designs are no better or worse than past designs, about 13 percent of the structures would fail at limit load. This value is three orders of magnitude higher than the highest value suggested in Table I. Therefore, analysis alone is considered inadequate for obtaining structural designs that will very rarely fail at limit condition.

The concept of error disclosure by strength testing is developed in Section 2.3d. The strength test is usually very effective in this capacity because the probability that a system such as B, E, or K in Figure 9 would pass a test to the design load and then fail at limit load is extremely low. Unfortunately, there is some probability that an underdesigned system such as System Q in Figure 10 will pass the strength test and be accepted for operation as shown in Figure 10. The larger the strength scatter (coefficient of strength variation), γ_s, the more likelihood that a test article that is much stronger than the mean strength will pass the test to be followed by failure of an operational vehicle that is much weaker than the mean.

The relationship between the test load necessary to reject understrength designs with a sufficiently high degree of certainty and the strength scatter is shown in Figures 24 and 25. The simple, deterministic action of successfully passing a strength test to loads determined by the Limit Test Factor of Safety shown on Figures 24 and 25 will assure that the probability of failure at limit condition will be consistent with the S.R. goal for the particular vehicle. In effect, this Limit TFS makes the necessary provision against understrength failures for each structural design.

In addition to the requirement that structures should rarely fail at limit conditions, it was stated that most of the structures should survive the omega condition. This requirement is related to insuring that the structure will meet the overall S.R. goal. Comparable problems of analytical error and certainty of error disclosure by test exist for the omega condition as for the limit condition. In order to insure that the structure will survive the omega condition with a degree of certainty compatible with the S.R. goal established for the vehicle, the structural system must be designed and tested to loads corresponding to the omega condition multiplied by the omega TFS defined in Figures 12 and 20. It should be understood that these omega loads do not necessarily have a factorial relationship to limit loads. Any nonlinearities in load between limit and omega should be accounted for. Any difference in temperature should be accounted for. Furthermore, there may be a difference in allowables and scatter factor, γ_s, associated with each limit and omega condition that should be recognized. The simple, deterministic action of passing a strength test to loads determined by the Omega Test Factor of Safety shown in Figures 12 and 20 will assure that the total probability of failure will be consistent with the S.R. goal for the particular vehicle and that most structural systems will survive the omega condition. In effect, this Omega TFS makes the necessary provision against overload failures for each structural design.

Restated, the new procedure requires the specification of two separate and distinct operational conditions, limit and omega. The first defines the situation where provisions against failures due to understrength must be

introduced. The second defines the strength that must be provided to handle overload situations. The factors applied to limit and omega loads are determined as a function of the strength scatter factor, γ_s. In all other aspects, the new procedure is very comparable to the Present System. By making these modifications, the new procedure has the capability to provide consistent level of structural reliability in varying circumstances. In particular, the desired S.R. can be maintained even when the strength scatter is increased to much higher values than have been common in the past.

Undoubtedly, even more important to the design of light weight but reliable structures is the ability to isolate each of the parameters that control the true structural reliability. By so doing, the design factors required to provide a given level of S.R. can be reduced to any desired value, provided that the structural configuration and the operational limitations are controlled accordingly. This cannot be done at present because the Factor of Safety in the Present System is not identified with any specific requirement for understrength or overload. Controlling one without the other will not necessarily maintain a desired level of structural reliability. Therefore, the effect of reducing the Factor of Safety in the Present System is not really determinable.

Explicit actions to minimize the structural design requirements while maintaining a desired level of S.R. are relatively simple. First, the performance requirements for the structural system must be minimized. As always, any reduction in the limit condition will result in a lighter weight structure. In the new procedure there is no specific relationship between limit and omega conditions. This permits the choice of an omega condition (which controls the overload capability of the structure) that is arbitrarily close to the limit condition. Such narrowing of the gap between normal, limit conditions and abnormal, omega conditions will require establishment of a new interface between structural and non-structural systems. Positive procedures must be established to control operations to insure that the operational limitations are not violated to the extent that an omega condition is attained by the vehicle. The narrower the gap between the limit and omega conditions, the more stringent must be the control of the operations.

Assuming that any reduction in the required design factors is not to be accomplished by reducing the structural reliability goal, the Test Factors of Safety given in Figures 12, 20, 24 and 25 present the key to possible weight reductions. In every case, the TFS required for a given S.R. goal can be reduced by reducing the strength scatter, γ_s, of the structure. Typically, the 1.5 FS used in the past has effectively covered the limit TFS requirement. As the ratio between limit and omega conditions is reduced, the Limit TFS will become controlling. At this point any further effort expended in controlling operational overloads would be futile unless the Limit TFS could be reduced so that less provision against understrength is needed. Besides the option to reduce the Limit TFS by reducing the strength scatter, the designer could reduce the Limit TFS by conducting multiple strength tests as indicated in Figure 25. All of this provides a rational means to justify the use of reduced design factors provided it is feasible (1) to control overloads, (2) to reduce the strength scatter, and (3) to conduct multiple strength tests.

The description of the new procedure to this point has been concerned with time-independent (static) strength situations. A complete quantitative structural design criteria by statistical methods must consider time-dependent (fatigue) strength situations. The basic approach for fatigue follows the same philosophy developed for the static situation. Only the details are different. However, implementation of this basic approach requires the adoption of a new concept of the failure mechanism in fatigue.

Residual strength rather than life is treated as the significant parameter in fatigue situations. In the static case, the probability of failure is a function of the strength of an individual structure being exceeded by a load sometime during the life of the vehicle. In the fatigue case, the same considerations govern. During any given time period in the life of the vehicle, the probability of failure is a function of the residual strength at that time and the probability that the loads experienced during the period will exceed the residual strength. This is identical to the static problem except that the period of time for which the strength can be considered unchanged is much shorter. There is a scatter in the strength at any given time, just as in the static case. The only difference between the static and fatigue situation is that the mean residual strength and the associated scatter in residual strength vary from one time period to the next. The lifetime probability of failure is simply the integration of the probability of failure in each separate period from the beginning to the end of the service life of the vehicle.

The new procedure assumes that the fatigue analysis is characterized by the same type of difficulties as the static problem. No matter what fatigue theory is used, it is expected that there will be as many or more occasions when the analysis does not correspond to the actual results as there have been for the static case. Therefore, a probability of failure, calculated on the basis of a no-error assumption, would be incorrect as discussed in Section 2.4d. Any reasonable assumption of the error function in fatigue, comparable to that shown on Figure 5 for the static case, would result in the determination of an unacceptably low S.R.

The fatigue test performs the same function as the static test in disclosing, by premature test failure, that there is an error in the analysis. The subsequent redesign and retest upgrades the S.R. just as the static test does. The problem is aggravated, however, by the large scatter in time of failure as illustrated by Figure 31. In general, a fatigue test does not disclose the errors with as high a degree of certainty as in the corresponding static situation. However, the computer program described in Volume III can determine the test life required to meet any given reliability goal. The test life for various types of fatigue test can be determined as shown on Figures 38 and 39. This factor on the service life is analogous to the static Test Factor of Safety shown on Figures 12 and 24.

c. Verification of Loads and Design Conditions

In addition to the necessity for strength tests to disclose error in the strength analysis, other tests are needed to verify the S.R. level attained in operation. Both the static and fatigue tests are conducted to loads determined

analytically for the specified operational conditions. These loads must be verified by flight and ground loads tests. Such tests would not represent any difference between the new procedure and the Present System except for the problem of verifying the omega condition loads. This is discussed in Section 2.3e.

Even if the structure has exactly the strength it was intended to have and even if the loads are absolutely correct, the actual structural reliability attained in service will not necessarily correspond to the S.R. goal. If the limit and omega conditions are encountered more often than was expected when these conditions were established as design conditions, the S.R. will be lower than desired. Once a vehicle with a structural system having a particular strength level is accepted and placed in service, the S.R. can be controlled by controlling the operations so they conform to the initially predicted operations. This can be accomplished by monitoring the actual operational results and comparing with the prediction used in choosing the limit and omega conditions. This monitoring can be accomplished in several ways. Simple reporting of the occurrences when the operational limitations were exceeded is one way. Instrumented operations such as provided by an eight channel recorder is another. It does not take an actual occurrence of an omega condition to decide that the operations are being conducted in a more severe fashion than anticipated. Section 2.3g(3) describes some of the appropriate procedures for "proving" that operations are compatible with the available strength in the structural system, as fabricated. A USAF contract[13] has developed a computer program that will print appropriate warnings whenever the operational usage is more severe than it should be. After a warning, the operations should be modified to reduce their severity so that the available structure can continue to be used. Alternatively, it may be decided to change the initial decision on the required structural performance and to increase the structural requirements to match the actual operations.

5.4 SUMMARY

The steps in the new procedure can be summarized as follows:

(1) Establish a structural reliability goal consistent with the mission of the vehicle. Table I values are suggested. The S.R. goal serves as the basis for the subsequent requirements, but the S.R. goal itself is not designated as a requirement.

(2) Choose limit and omega design conditions. These should be based on the S.R. goal as indicated on Table I. If the necessary statistical data are not available, qualitative considerations may be used as the basis for the choice. A limit condition should be a normal or expected operational condition. Where appropriate, it will correspond to an operational limitation of the vehicle. As such, it corresponds to the limit condition in the Present System. The omega condition should be an abnormal operational condition, one reached only as the result of an error in operation or in the functioning of a non-structural system. The omega condition represents the upper bound of any required structural capability. If the structure should fail due to operations beyond omega, it has effectively been predetermined that the operational problem should be corrected rather than that the structural system should be modified to tolerate the operational error.

(3) The structural system's performance requirement is based on statistical considerations. However, the intention of the requirement is to define a structural system that will never fail at a limit condition, a system which will usually survive the omega condition and a system which is expected to fail beyond the omega condition.

(4) The basic design is qualified and approved in much the same fashion as in the Present System. Analytically, the allowable strength of the structure must be equal to or higher than the loads corresponding to the limit condition loads multiplied by the Limit Test Factor of Safety presented on Figures 24 and 25. As a separate and distinct requirement, the allowable strength of the structure under the omega conditions must be equal to or higher than the loads corresponding to the omega loads multiplied by the Omega Test Factor of Safety presented on Figures 12 and 20. For fatigue situations the structure must be designed to survive to a multiple of the nominal life as defined by Figures 38 and 39.

(5) As in the Present System, the strength analysis must be verified by strength tests. In the static cases, Figures 12, 20, 24 and 25 define the test loads. In the fatigue cases, Figures 38 and 39 define the fatigue test duration.

(6) Design loads in the new procedure must be verified much as in the Present System.

(7) Service operations should be monitored by procedures discussed in Section 2.3g(3) to determine that the operations are consistent with the design limit and omega conditions. If not, either the operations must be changed to make them consistent with the design conditions, the structure must be changed to be consistent with the actual operations, or the structural reliability goal must be changed.

SECTION VI

DEMONSTRATION OF THE STRUCTURAL DESIGN CRITERIA METHOD

USING F-100 DATA

6.1 GENERAL

The new procedure developed in this report for defining statistically-based, deterministic structural design criteria is applied to the F-100 airplane. This airplane is a modern service aircraft that has enjoyed volume production and wide service usage. Comprehensive records documenting the design parameters and the operational record of this airplane are available. Accordingly, the F-100 represents an excellent vehicle for demonstrating the new procedure.

6.2 BACKGROUND INFORMATION

a. F-100 History

The F-100, used as the model for this demonstration, has been produced in quantity through four different models and has been in the Air Force inventory for over 12 years. F-100 squadrons are currently engaged in the Vietnam war where they have been deployed at several different air bases since October of 1964.

The F-100 engineering design effort began on the prototype "Sabre 45" as a company-sponsored program on January 19, 1951. On May 14, 1951, North American proposed to the Air Force to construct two Sabre 45 air superiority fighters to provide early combat availability of production airplanes. The first letter contract for two prototypes was issued November 1, 1951. On December 7, 1951, the Air Force officially designated the Sabre 45 the F-100A. The first production contract, January 25, 1952, was for 23 F-100A airplanes, one static test article, spare parts, etc.

The YF-100 airplane was first flown on May 25, 1953, and exceeded the speed of sound in level flight. The last production F-100F was made in September 1959. By February 1959 more than 7174 flights, totaling over 4907 hours, had been made by NAA engineering test pilots.

b. Structural Design Criteria and Operating Limitations

The F-100 is a Class II day fighter with fighter bomber capabilities. It has a level flight high speed of Mach 1.35 at the optimum altitude of 35,000 feet and a service ceiling of 55,000 feet. The 25 percent chord lines of all lifting surfaces are swept back 45 degrees. The flight control surfaces are all actuated by irreversible hydraulic boost systems. It is powered by a Pratt and Whitney axial-flow turbojet engine with afterburner (J-57-21). The landing gear is a conventional tricycle type equipped with air-oil shock struts. The A, C, and D models, single place, were designed to

USAF Specification C-1803,[19] and the F model, two place, to Military Specification MIL-S-5700.[20] This means the F-100 design is based on the procedures of the Present System with a Factor of Safety as designated in the specification and with no requirement to achieve a quantitative structural reliability number. Also, there was no requirement to survive a specified number of service hours.

The structural design limit load factors, gust velocities and landing sink speeds are shown in Tables III, IV, and Figures 57, 58, 59 and 60.

TABLE III

MANEUVER LOAD FACTORS

Applicable Weight Condition	Symmetrical		Unsymmetrical	
	Pos.	Neg.	Pos.	Neg.
Weights equal to or less than the structural design gross weight without external stores	7.33	3.00	4.88	1.00
Weights greater than the structural design gross weight and all weights with external stores	6.00	2.00	4.00	1.00

Equivalent gust velocity of 50 fps up to V_H. Landing sink speed A, C, D models v_s = 12 fps ultimate with energy requirement of 0.9 (n-1) W_j. Landing sink speed for F models v_s = 9 fps.

TABLE IV

LANDING LOAD FACTORS

Applicable Weight Condition	Main Gear	Nose Gear
Landing Gross Weight	3.0	3.0
Take-off Gross Weight	2.0	2.0

As noted, there was no contract requirement for a specified number of hours on airplane service life. However, as an outgrowth of F-86 experience, the unofficial F-100 figure used at the time of design was 2000 hours. Elements,

parts, and assemblies in the design development phase of the program were tested cyclically to constant load levels. Usually the tests were considered complete at 3000 hours, which is related to the 50 percent safety factor. There was no concerted effort to design the airplane for a certain number of hours; however, there was a conscientious awareness of good engineering practice to avoid stress risers and fatigue-prone structures.

The following charts illustrate the design and operating envelopes of the airplane. The speed-altitude profile, Figure 57, depicts the flight envelope of the airplane. These design values have been verified in numerous flight test programs over the years and more recently by Air Force energy-maneuverability studies wherein comparisons are made with contemporary airplanes. The V-n diagrams, Figures 58 and 59, are typical of these used for structural design at two altitudes. The operating flight limits for each letter model in the fleet are displayed in Figure 60.

c. Structural Integrity Tests

The flight test programs on the F-100 airplanes were very comprehensive. In addition to the customary tests on stability and control, performance, power plant, dives, etc., the structural integrity of each letter model was demonstrated in flight. As a supplement to this, the flight loads were measured on a specially instrumented airplane. The maximum service limits on airspeed, control usage, and load factor were established by these structural demonstrations and flight loads programs.

Complete airframe static tests were performed at the Contractor's plant on the F-100A. Static tests of significantly changed components for each succeeding letter model were accomplished as they were introduced into production. Extensive structural testing of fittings and components for both static and repeated loadings were a vital part of the design development cycle of the airplane. A complete airframe laboratory fatigue test for a 5500 hour service life, which is part of an AF Structural Integrity Program, is presently being accomplished at the Contractor's plant. A failure in the wing root occurred at 4674 hours. It should be noted that the ASIP studies later showed the loading spectrum used in the test to be too severe. As discussed in Section 6.4d a revised spectrum was established on Figure 75 and the tests were resumed. Another test was conducted on a wing that had accumulated a significant number of operational hours before the test. An F-100 T-Bird Solo airplane (serial #55-2724) experienced a mid-air collision January-February 1963 wherein the wing sustained minor damage. This wing, Table IX, No. 1, had 1080 flight hours in the T-Bird fleet, when it was replaced and later returned to the contractor. As discussed in Section 6.4b, the load factor spectrum of the "Thunderbird" aircraft is more severe than that experienced in normal service operation. On January 31, 1967, this T-Bird wing sustained 150 percent of the maximum design limit condition in a static test as a part of the ASIP at the contractor's plant.

The following values for F-100 allowable limit load factors and load at key points (Table V) have been verified by comprehensive structural testing, both in flight and in the laboratory over the years.

$-2.0 < N_x < 4.5$ $\qquad$ $N_y = |3.0|$ $\qquad$ $-3.0 < N_z < 7.33$

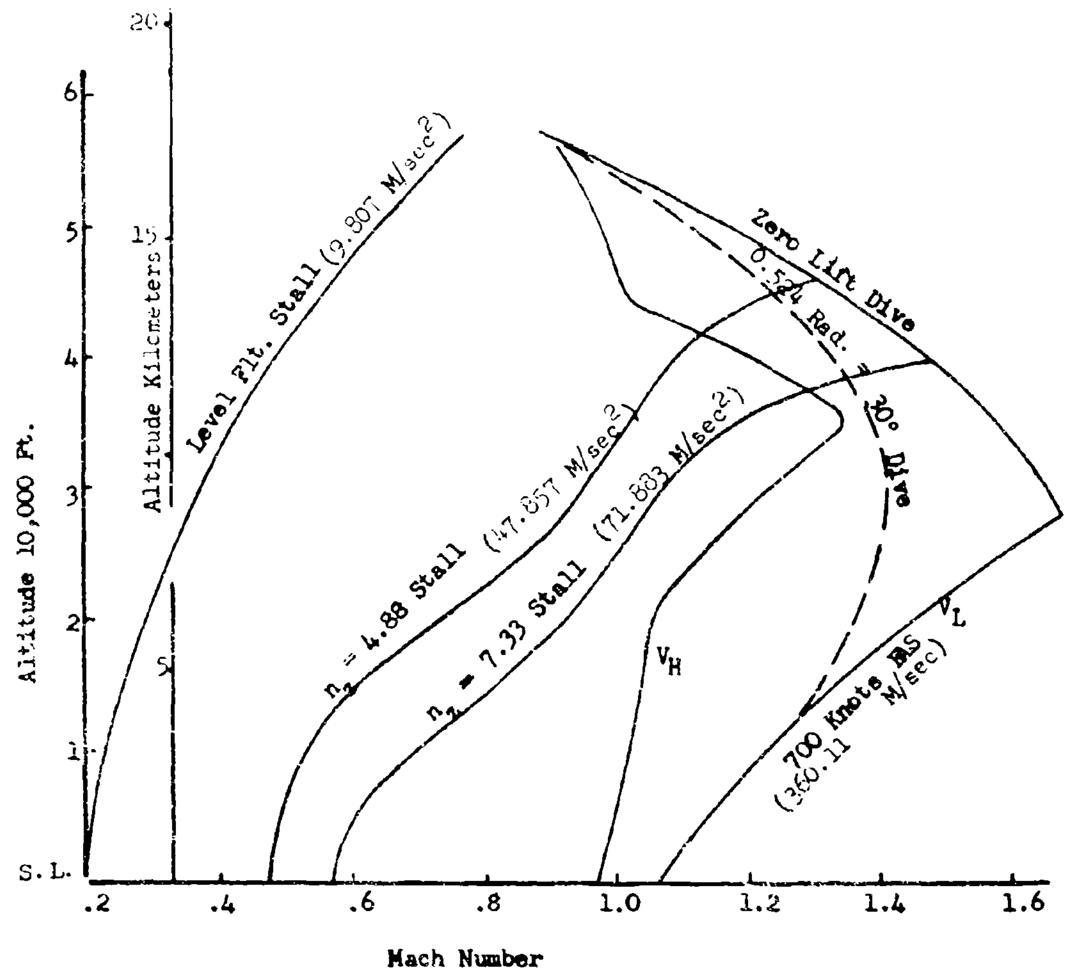


FIGURE 57. F-100 SPEED-ALTITUDE PROFILE

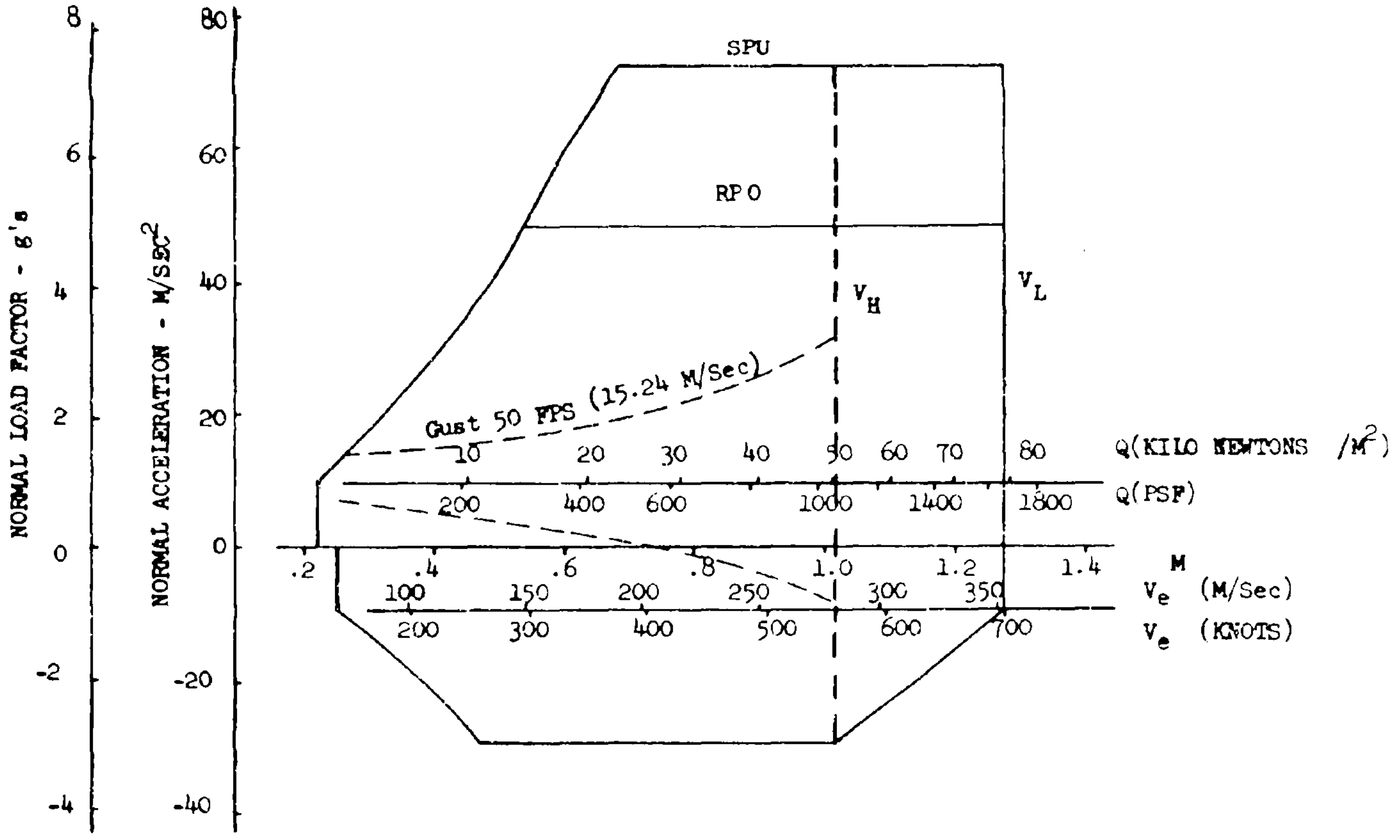


FIGURE 58. F-100 V-N, M-N, Q-N DIAGRAM AT 10,000 FEET (3048 KILOMETERS)

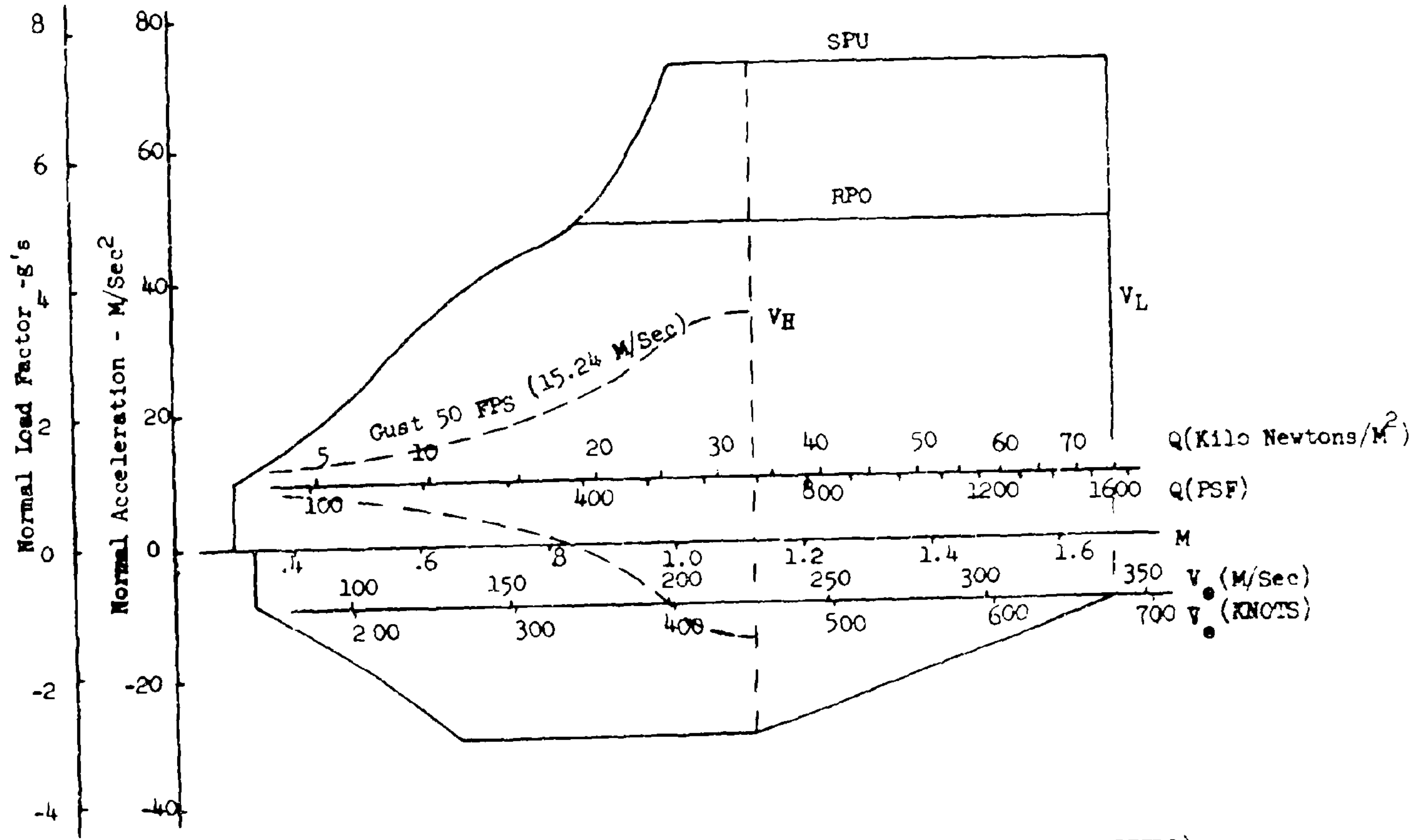


FIGURE 59. F-100 V-N, M-N, Q-N DIAGRAM AT 25,000 FEET (7620 KILOMETERS)

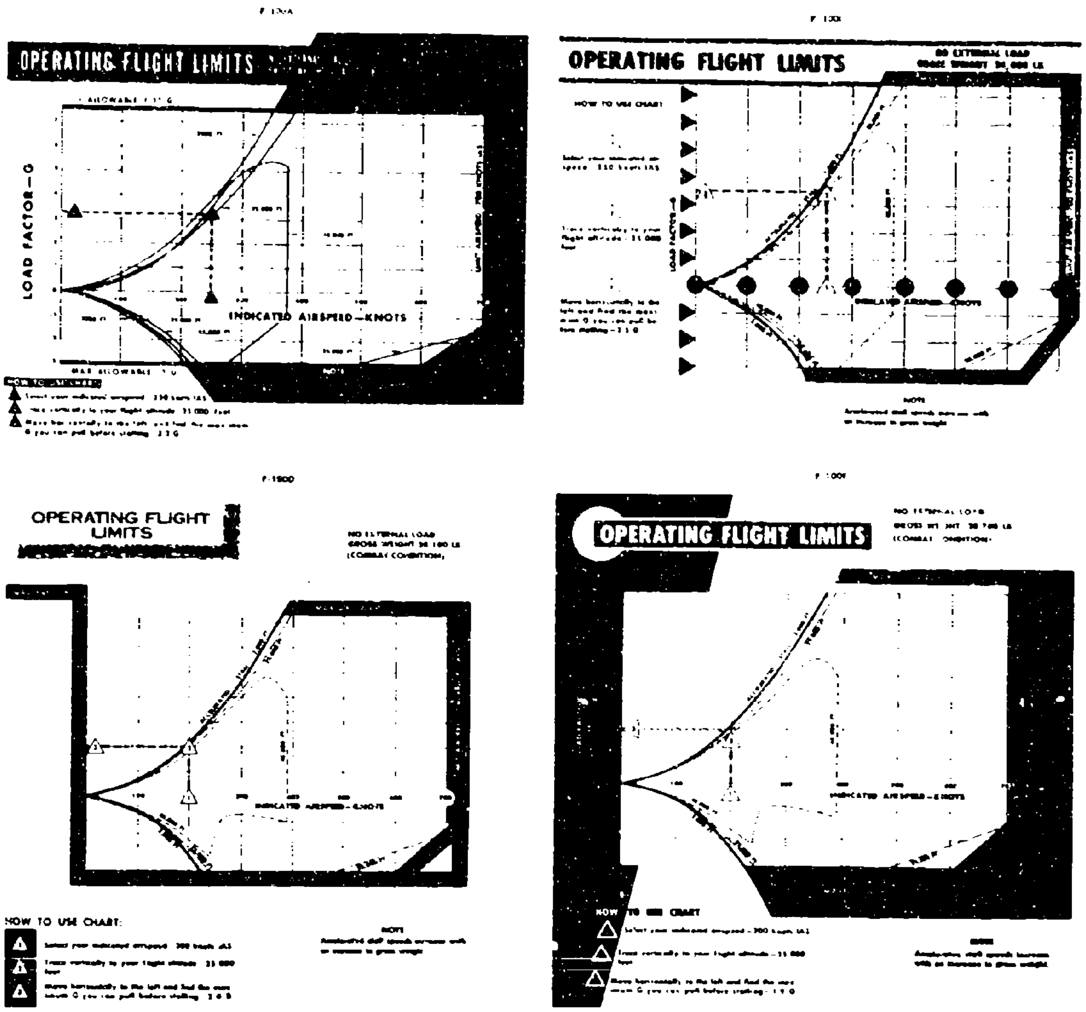


FIGURE 60. F-100 OPERATING LIMITS

TABLE V

ALLOWABLE LIMIT BENDING MOMENTS

Item	Location	Bending Moment* $(10)^6$ in-lbs	
		M_x	M_z
Wing Root	B.P. 21.	8.0	
Wing Mid Span	Sta. 145	2.73	
Hor. Tail Root	Sta. 29	0.64	
Ver. Tail Root	Fus. Sta. 465 W.P. 20	0.68	
Fus. Fwd	180	1.86	1.25
Fus. Rear Spar	310	8.85	2.58
Fus. Field Br'k	369	5.48	2.08

*Note - The Fuselage B.M. are not simultaneous

F-100 SINGLE LOAD PATH POINTS
(Possibly Fatigue Critical)

Wing - fuselage splice joint, fillet radius in cover plate at root rig diagonal spar.

Horizontal tail cover plate attach at heavy yoke pipe tie across fuselage.

Fuselage field break point.

Vertical tail main beam coat hanger fitting.

Main gear - axle and upper trunnion

Nose gear - upper drag brace link, integral cylinder for downlock. Not serious after crack develops.

6.3 STRUCTURAL FAILURE DATA

a. Maintenance Records

In an effort to utilize all available information, an attempt was made to incorporate AF 66-1 Maintenance Data in the determination of the strength distribution. A representative tape[21] containing F-100 aircraft maintenance records for three months of operation (January-March, 1965) was used.

The procedure was to first sort out primary structural items on the aircraft. Using these data, a second sort was made to eliminate types of malfunctions not pertinent to structural failure, i.e., electronic equipment malfunctions, engine failure, etc. The remaining data were then sorted by model series (D or F), type of malfunction, work unit (primary structural item), aircraft serial number, and flight hours accumulated by the aircraft.

In the three months of data considered, a total of 168,000 maintenance records had been compiled. Of these records, 16,000 were considered to be possibly pertinent to primary structure malfunction. Obviously, the need arises to separate minor malfunctions from critical failures. Herein lies the problem. As yet, no method has been devised to pinpoint the relatively few critical failures in the mass of malfunction records.

Table VI presents a record of the data on wing primary structure with malfunctions labeled "broken." For the F-100 D model, 51 such records are listed for the three month interval, requiring roughly 60.4 total hours of maintenance for an average of about 1.2 hours per malfunction. Two malfunctions required more than three hours of maintenance. Based on these data, the only obvious approach to the problem would seem to be based on the hours of maintenance time required. This criterion hardly seems valid since replacement of a critical piece of structure or fastener could conceivably require only a matter of minutes. Other approaches based on "action taken" codes and "when discovered" codes seem equally futile.

It is therefore concluded that a judicious review of the actual maintenance reports would be required to isolate critical failures reported in AF 66-1 data. This procedure is necessitated mainly by lack of more precise definition and terminology in the AF 66-1 data coding system.

However, numerous other sources provide adequate identification of deficiencies in the structural components of the aircraft. Among these are:

1. Engineering Unsatisfactory Reports, which detail deficiencies discovered generally by the ground crew or during periodic inspections.

2. Tear-down Deficiency Reports, the results of structural components being forwarded to a prime depot and torn down for detailed failure analyses.

3. Incident Reports, in which no major damage to the aircraft has resulted.

4. Accident Summary Reports, filed in case of major damage to, or destruction of, the aircraft.

Table VII presents a summary of wing-fuselage attach bolt failures. Table VIII presents a summary of in-service cracks of possible fatigue origin. Report No. DS 65-1[22] presents a deficiency summary of structural and non-structural components of the fuselage, wing, and vertical stabilizer of F-100 aircraft. These summaries have been compiled from sources as listed

TABLE VI

AF 66-1 MAINTENANCE DATA EXAMPLE

Work Unit - Wing Primary Structure
How Malfunctioned - Broken

Work Unit Code	Action Taken Code	Number of Malf.	Hours of Maintenance for Each Malfunction										Totals
			(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	
11510	G	1	1.0										1.0
11511	G	4	0.6	1.0	1.0	0.5							3.1
11513	G	2	2.0	3.0									5.0
11515	G	10	3.0	0.3	1.5	0.2	2.5	2.0	0.5	0.7	1.2	6.3	18.2
11516	P	1	0.5										0.5
	G	3	1.8	1.0	0.5								3.3
	F	1	.0										.0
11517	G	5	0.5	1.0	1.0	0.5	0.3						3.3
11518	G	3	0.5	0.5	0.5								1.5
	F	2	.0	0.7									0.7
11519	P	1	1.9										1.9
	R	4	0.8	1.5	0.7	0.5							3.5
	G	2	0.4	2.0									2.4
1151A	G	8	1.4	0.5	1.0	0.8	1.0	0.6	1.5	0.7			7.5
	P	1	2.0										2.0
	R	1	0.5										0.5
	F	1	6.0										6.0
1151B	F	1	.0										.0
Totals		51											60.4

Work Unit Code

11510	Structure (Primary)
11511	Wing Assy.
11512	Center Section Assy.
11513	Outer Panel Assy.
11514	Spar Assy.
11515	Leading Edge
11516	Trailing Edge
11517	Tip Assy.
11518	Skin
11519	(Not otherwise coded)
1151A	Panel Assy.
1151B	Rib Assy.

Action Take Code
(Excluding shop work)

F	Repair
G	Repair and/or Replacement (minor)
P	Removed
R	Removed and Replaced

TABLE VII

WING-FUSELAGE ATTACH BOLT FAILURES

A/C Model	A/C Hours	Base	Problem
F-100D 56-3006	2803	Bien Hoa	RH aft bolt broken
F-100F 56-3925	2990	Bien Hoa	RH aft bolt broken
F-100D 56-3187	2022	Bien Hoa	RH aft bolt cracked
F-100F 56-3775	2401	Bien Hoa	RH aft bolt cracked
F-100F 56-3954	2668	Bien Hoa	RH aft bolt cracked
F-100D 56-3372	2256	Bien Hoa	RH aft bolt cracked LH aft bolt cracked
F-100D 56-3087	2660	Bien Hoa	LH aft bolt cracked
F-100D 56-3383	2772	Bien Hoa	RH aft bolt cracked
F-100F 56-4002	3054	Bien Hoa	RH aft bolt cracked
F-100D 56-2914		Bien Hoa	RH aft bolt cracked
F-100F 56-3975	3044	Bien Hoa	RH aft bolt cracked
F-100D 55-3618	2713	Bien Hoa	Bolt cracked
F-100D 55-2889	2530	Bien Hoa	Bolt broken and aft attach hole cracked

TABLE VIII

IN-SERVICE CRACKS (POSSIBLE FATIGUE ORIGIN)

A/C Serial Number	Date	A/C Hours	Location, Size, Remarks (Skin fillet at root rib and diagonal spar)
55-2724 F-100C T-Bird Solo		1080 ①	Right-hand lower 8 inches long.
55-2723 F-100C T-Bird Solo	2-17-64	2569	Right-hand and left-hand lower skins 8 inches long, right-hand upper skins 1/4 inch long.
55-2724 F-100C T-Bird	2-4-64	A/C 2418 1080 ① 1338 Wing	Right-hand upper skin (192-14140) crack length 1/2 inch.
55-2728 F-100C T-Bird	2-14-64	2800	Right-hand and left-hand upper skin (192-14140) crack length 1/2 inch.
55-2722 F-100C T-Bird	2-17-64	1661	Right-hand upper skin (192-14140) crack length 1 1/2 inch.
55-2874 F-100D	1-28-66	2641	Left-hand upper skin 3/8 inch long. 223-14140
56-3153 F-100D	3-25-66	2547	Right-hand upper skin 3/8 inch long. 223-14140
56-3038 F-100D	5-16-66	2425	Right-hand upper skin.
56-3119 F-100D	5-25-66	2605	Right-hand upper skin.
54-2075 F-100C	7-6-66	2464	Right-hand upper skin 1/8 inch long.
54-2039 F-100C ANG	7-23-66	2570	Right-hand upper skin two cracks 1/16 inch long.

(Continued)

TABLE VIII. (Continued)

A/C Serial Number	Date	A/C Hours	Location, Size, Remarks (Skin fillet at root rib and diagonal spar)
55-3639 F-100D	2-25-66	2419	Skin rabbet at root rib and L.E. rib 96. Left-hand upper skin 1 1/2 inch long. FS 257 223-14140
55-3558 F-100D (PACAF)	1965	Unkn.	Rear spar main landing gear trunnion support.
F-100D Unknown (French)	1964	Unkn.	Rear spar main landing gear trunnion support.
56-3650 F-100D	1-22-61	707	Rear spar main landing gear trunnion support.
54-3561 F-100D T-Bird	3-17-66	2233	Fuselage side skin F.S. 315 WL 12. Right-hand side 8 inches - 10 inches long terminates at upper longeron.
F-100D & F-100C	Prior 5-6-65		65 cracked upper NLG drag links (180-34120), 12 condemned, 349 aircraft inspected and reworked per T.O. 1F-100-964.
55-3703 F-100C	8-23-66	1926	Wing station 140 near M.G. door hinge.
55-3794 F-100C	8-23-66	1943	Wing station 140 near M.G. door hinge.
55-3708 F-100D T-Bird	1-3-67	2764	Wing right-hand upper cover plate fillet radius at root rib 1/8 inch long. This A/P entered the T-Bird fleet on 7-16-64 with 1838 hours.
56-3098 F-100D Yankee #1 Lead-the-fleet	1-16-67	2754	Wing right-hand upper cover plate fillet radius at root rib 3/16 inch long.

(Continued)

TABLE VIII. (Concluded)

A/C Serial Number	Date	A/C Hours	Location, Size, Remarks (Skin fillet at root rib and diagonal spar)
54-2199 F-100D Vaerloese, Den.	1-31-67	1689	Cracked wing root rib (192-12371) at left-hand forward wing-fuselage attach point
54-2222		2039	
54-2266		2099	
54-2270		2052	
54-2274		2088	
55-2769		1909	
55-2771		1828	
55-2779 F-100D Vaerloese, Den.	1-31-67	2098	Cracked wing root rib (192-1271) at left-hand forward wing-fuselage attach point.
55-3520 F-100D T-Bird	4-5-67	2600	No. 2 Solo T-Bird A/P. Cracks 3 1/2 inches long in lower surface cover plates on both left and right wings. They begin at the root rib forward center radius, proceed on a 45 degree angle for one inch to the first line of bolts, then change direction to the rear and stop at the second line of bolts. This A/P entered the T-Birds on 7-16-64 and accummulated about 1000 hours in the squadron.

① Wing replaced at 1080 hours, repaired at 1338+ hours.

above. Table IX is a special summary of wing root skin fillet area service fractures which have been dubbed "Thunderbird" cracks.

It must be concluded from this examination of maintenance records that this type of data cannot be satisfactorily correlated with structural reliability predictions. The structural reliability calculations are based on catastrophic failures during operations not the relatively minor failures detected during maintenance. Therefore, data of this type will not be examined further in demonstrating the new procedure.

b. F-100 Accident Records

There are voluminous records available which furnish much information on F-100 accident statistics. Unfortunately, these data are not organized in such a fashion as to readily identify those accidents which should be classified as structural failures. However, with the data available useful deductions concerning the structural failure rate can be made.

The following F-100 Aircraft Accident Summary reports for the time periods listed are available at the Contractor's facility. Their source is the Directorate of Aerospace Safety, Norton Air Force Base, California.

Time Period	Summary No.
1-1-65 through 12-31-65	7-66
1-1-63 through 12-15-63	15-64
Calendar year 1961	7-61
Calendar year 1960	7-61
7-1-59 through 12-31-59	3-60
1-1-59 through 6-30-59	13-59
Calendar year 1957	9-58
1-1-54 through 9-12-55	39-55

The following is quoted from NR 7-66:[23]

"F-100 Aircraft (A, C, D, and F) are active in several foreign air forces; however, this summary is concerned only with those possessed by the USAF and the Air National Guard.

"The F-100 has been operational for over 12 years and has accumulated more than 3,300,000 flying hours. There are tactical units in TAC, USAFE, PACAF, ANG, and ADC. The Tactical Air Command also provides rotational units to certain overseas areas. During 1965, F-100 combat crew training was conducted by the Tactical Air Command at Luke AFB, Arizona. In 1965, as in 1964, the F-100 flew over 300,000 hours. These hours encompassed a wide spectrum of fighter activities; long over-water flights, conventional bombing and gunnery (day and night), various types of special weapons delivery, student training, and combat support in Southeast Asia.

TABLE IX

FATIGUE CRACKS - WING ROOT SKIN FILLET
"Thunderbird" Cracks - ASIP

No.	Date Report	Model and Serial No.	Location Left-hand Lower	Location Left-hand Upper	Location Right-hand Lower	Location Right-hand Upper	Airframe Service Hours	Using Command
1	1 Sep 59	C-55-2724			6"		1080 ①	T-Bird Solo
2	10 Jul 63	C-55-2723	5"	2"	8"	1/16 sev	2569	T-Bird
3	15 Mar 64	C-55-2724				1/2	1338+ ①	T-Bird Solo
4	15 Mar 64	C-55-2728		1/4		1/4 sev	2801	T-Bird
5	15 Mar 64	C-55-2722				2"	1661	T-Bird
6	early 65	unknown				1/4	unknown	TAC
7	late 65	D unknown				1/4	unknown	TAC
8	18 Jan 66	D-55-2874		3/8			2613	401 TFW
9	21 Mar 66	D-56-3153				1/4	2547	3 TFW Eng. AFB
10	16 May 66	D-56-3038				1/16"	2425	4510 CCTW Luke
11	25 May 66	D-56-3119				3/8"	2605	31 TFW Homest.
12	9 Jul 66	C-54-2075				1/4"	2464	ANG 150 TFW Andrews
13	23 Jul 66	C-54-2039				1/16 2cr	2569	4510 CCTW Luke
14	17 Nov 66	C-54-2039				1/8	2605	ANG Kirtland
15	2 Dec 66	D-56-2935		3/4			2505	4510 CCTW Luke
16	5 Jan 67	D-55-3776		1/8			2764	T-Bird
17	13 Jan 67	C-54-1970				1/2	2861	ANG Lambert
18	15 Jan 67	D-56-3098				3/16	2754	Yankee #1 SMAMA-Eng.
19	25 Jan 67	C-54-1953		1/32			2547	ANG 140 TFG
20	2 Feb 67	C-54-1773		1/4 4cr			2291	ANG 177 TFG Atlc. City
21	10 Mar 67	C-54-2058		3/4			2635	ANG Andrews
22	10 Mar 67	C-54-1740				1/32	1994	ANG Kirtland
23	10 Mar 67	D-56-3093				3/8	2609	OMS Luke
24	21 Mar 67	C-54-1860		unknown			1868	
25	22 Mar 67	C-53-1746				1/16	2348	ANG
26	3 Apr 67	C-53-1757		1/16				
27	4 Apr 67	D-56-3520	3"		3"		2600	T-Bird Solo ②
TOTALS	27 incidents 23 aircraft		2	10	3	17	Average hours 2367	

① Wing replaced at 1080 hours, repaired at 1338+ hours
② 1010 hours, T-Bird time

"During its operational life, the F-100 has experienced 933 major accidents. In spite of its age, the F-100 is still the work horse of the tactical air forces. For this reason, and because of its extended service life, all possible actions are being taken to provide greater safety for the aircrew. Modifications continually are being made to both airframe and engine to increase reliability. These modifications are the result of material deficiences identified by EUR's, AFM 66-1 data, incident reports, TDR's and accident investigations. During 1965, Project High Wire was completed on all F-100D's and F's. This program consisted of completely replacing all aircraft wiring and connecting points. Some outstanding TCTO's were accomplished concurrently."

TABLE X

F-100 MAJOR ACCIDENTS

Year	Major Accidents	Year	Major Accidents	Year	Major Accidents
1953	0	1958	168	1963	52
1954	4	1959	125	1964	47
1955	22	1960	94	1965	44
1956	70	1961	82	Total to 1965	933
1957	160	1962	65		

TABLE XI

PRIMARY CAUSE FACTORS OF MAJOR AIRCRAFT ACCIDENTS (F-100)

Total	933
Pilot	260
Other Crew	0
Supervision	35
Maintenance	68
Other Personnel	19
Material Failure	379
Airbase and Airways	11
Weather	2
Misc. Unsafe Cond.	19
Undetermined	140

Accident rates for a seven-year period were compiled in Reference 24. The resulting graph is reproduced as Figure 61. The flattening and possibly reversing trend of the accident rate curve during the last three years is attributed to combat action in Vietnam.

The accident totals shown on Table X and the accident rates shown on Figure 61 are for accidents due to all causes. The primary cause factors for these accidents is presented in Table XI, taken from Reference 23. The 379 accidents classified as material failure are of particular concern to a structural reliability study. Examination of the accident reports indicates that less than 10 percent of these "material failure" accidents represent what is usually considered to be a structural failure. Unfortunately, it is not possible to be very precise in defining the number of structural failures. The best that can be done at this time is to establish upper and lower bounds for the number. These bounds can be used to validate the number chosen as the most logical value to represent the number of F-100 structural failures.

More than two structural failures (usually due to excessive load factors) can be documented. This represents 0.1 percent of the original fleet of 2292 airplanes (see Table XII). It must be concluded that this represents the lower bound. The 379 "material failure" accidents represent the upper bound and about 16 percent of the original fleet. All things considered, it appears that 20 failures is a reasonable number to attribute to structural failure. This corresponds to a one-in-one-hundred failure rate. This is considered to be comparable to the rate attained with 6277 F-86 series airplanes and over 12,000 P-51 series airplanes. Twenty failures will be used in determining the actual structural reliability of the F-100 series. This value in turn, will be used in the comparison with the calculated values determined by the computer programs as described in Section 6.5.

c. Inventory Data

In order to determine the failure rate and the structural reliability of the F-100 in service, either the total numbers of vehicles involved or the total number of flying hours must be known. Table XII presents a compilation of the original and remaining inventory of F-100 series airplanes. Inventory data for other century-series fighters is presented in Table XIII for comparative purposes.

TABLE XII

F-100 INVENTORY

Model	Original	Remaining 2-1-67	USAF 2-1-67	MAP* 2-1-67
F-100A	203	115	55	60
F-100C	476	262	262	—
F-100D	1274	740	605	135
F-100F	339	235	208	27
Totals	2292	1352	1130	222

* Military Assistance Program (NATO)

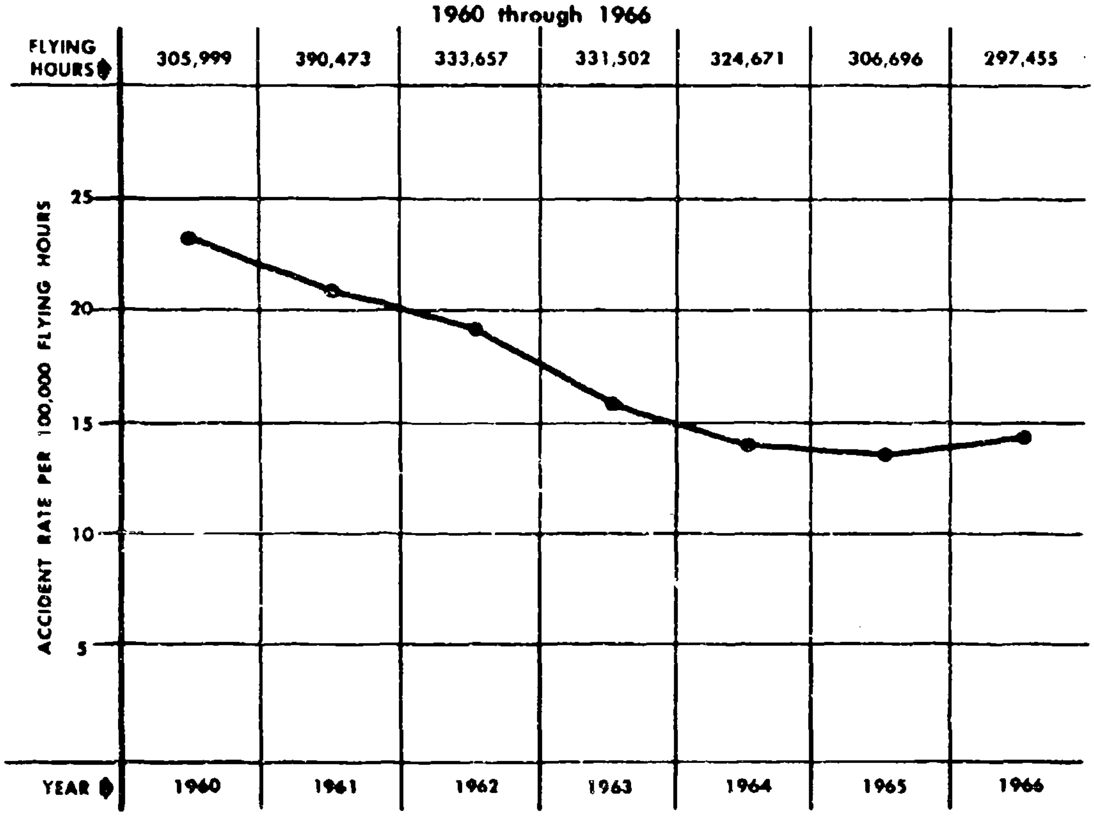
A Review of the F-100's for 1966

F 100 SERIES It should be of interest to the using commands, as well as to pilot and maintenance personnel, to know how the F-100 Series Airplanes fared during 1966. Here are some statistics:

The F-100 Series Airplanes accumulated 297,455 hours during the year 1966. This figure brings the total flying hours for the Century Birds to approximately 3,786,210 flying hours since their introduction into the Air Force inventory.

The F-100's are averaging over 2500 hours per airframe, with some airplanes over the 3000-hour mark. Although these figures make pleasant and interesting reading, other figures do not. For instance, in 1966, F-100 Series Airplanes were involved in 45 major accidents, 40 of which resulted in the loss of the airplane. Fourteen pilots lost their lives in these accidents. Also, substantially damaged airplanes represent a heavy work load to repair activities.

F-100 ACCIDENT RATES AND FLYING HOURS
1960 through 1966



MARCH 10, 1967

FIGURE 61. F-100 REVIEW - 1966

TABLE XIII

INVENTORY OF OTHER CENTURY-SERIES FIGHTERS
(As of 1 February 1967)

Model	Number
F-101	520
F-102	743
F-104	121
F-105	494
F-106	282
F-4	1126

It is noted on Figure 61 that the total fleet hours for the F-100 series airplanes, since their introduction into the Air Force inventory, is 3,786,210. The distribution of these hours among individual airplanes of the fleet in 500-hour blocks is indicated on Table XIV.

TABLE XIV

F-100 LOGGED SERVICE HOURS
(As of 2 March 1967)

Hours Block	500-1000	1000-1500	1500-2000	2000-2500	2500-3000	3000-3500
USAF Inventory (All letter models)	6	28	168	621	263	21

6.4 LOADS SPECTRA

a. ASIP Program

The United States Air Force plans call for retention of the F-100 series airplanes on active status well into the 1970's. These plans make it very obvious that the airplanes will be flown well beyond the life expectancy anticipated in the original design and development stages of the structure. The average F-100 has 2500 service hours today. Consequently, the USAF contracted with North American Aviation, Inc. to perform an "Aircraft Structural Integrity Program" which will demonstrate a 5500 hour service life capability for the F-100 when certain structural modifications are made to the airframe.

The data collection for Phase I of the Aircraft Structural Integrity Program (ASIP) began in March 1966 and ended in August 1966. The loads data were obtained from 122 aircraft equipped with statistical accelerometers.

Table XV presents a detailed breakdown of these airplanes by model, tail number, service hours, code, date instrumented, and base location. Four of these airplanes, code-named Yankee #1, #2, #3, and #4, were also equipped with velocity-load factor-altitude (VGH) instrumentation and tape recorders to measure bending moments on lifting surfaces and the fuselage, and landing gear loads. A sample, "Pilot's and Crew Chief's Log" used in gathering the usage statistics is shown, Figure 62. The Phase I data, which is used in this report, was based on 3308 hours of statistical accelerometer data, 200 hours of VGH data, and 113 hours of strain gage loads. The data are published in Reference 25.

Subsequent to the completion of Phase I of the ASIP, additional data was gathered on the F-100 operations, both in peacetime usage and in combat in Vietnam. Most of the statistical analyses in the following section are based on the Phase I data, but the additional data are presented where available. The ASIP airplanes which have been deployed to Vietnam bases and have engaged in combat are listed on Table XVI.

b. F-100 Load Factor Spectra

The load factor spectra used in demonstrating both the static and fatigue structural reliability programs are from the Phase I data.[25] These data for the normal and lateral load factors are presented on Figures 63 and 64. Additional normal load factor data, extending from the end of Phase I to May 1967, have been processed and are shown on Figure 65 as peacetime data. The spectrum for the 4322 hours in the extended period is very little different than that for the Phase I period. Also, shown on Figure 65 are the combat usage data from the airplanes in combat usage in Vietnam as listed in the previous section. This combat usage data, although from a relatively small sample, is significantly more severe than the peacetime spectra. It will be recalled that the load factor data from the Korean war[26] were high, also, and led to the 8.67 g Air Force requirement for Class I fighters.

From the Phase I data, Figure 63, it is seen that the limit design load factor (7.33 g's) is exceeded 140 times every 5500 hours. This amounts to 0.0254 exceedances per hour, or one exceedance of limit every 39.3 flying hours. Since the average flight duration is one and two-thirds hours, the limit load factor is exceeded once every 23½ flights, on the average.

The combat usage design limit normal load factor spectrum, Figure 65, shows that the limit (7.33 g's) is exceeded 550 times every 5500 hours. This is equivalent to 0.100 exceedances per hour, or one exceedance of limit every 10.0 flying hours. Using the same average time of one and two-thirds hours for each flight, this results in an average limit load factor exceedance once every 6.0 flights in the Vietnam war. It will be recalled that the limit load factor is one "...which establishes a strength level for design of the airplane and components and is the maximum load factor normally authorized for operations," according to paragraph 6.2.4.4 of MIL-A-8860.[27]

The loading spectra, developed from the ASIP flight data, are maneuver-type spectra with the gust effects superimposed. The final load factor spectra, Figures 63 and 64, are a composite of all bases except Nellis AFB.

TABLE XV

F-100 LEAD-THE-FLEET AIRCRAFT

Code	Tail No.	Hours[1]	Date
	Cannon AFB		
Y1	56-3098(D)	2527	9/65
Y3	55-3804(D)	2213	3/66
X	55-3811(D)	2241	1/66
X	55-3562(D)	2389	3/66
X	56-3993(F)	2594	3/66
Z	55-3545(D)	2134	5/66
Z	55-3555(D)	2574	5/66
Z	55-3570(D)	2240	5/66
Z	55-3574(D)	1992	5/66
Z	55-3585(D)	2292	5/66
Z	55-3628(D)	1926	5/66
	Luke AFB		
Y2	56-3141(D)	2574	9/65
Y4	55-3755(D)	2603	3/66
X	56-2968(D)	2597	3/66
X	56-3140(D)	2621	3/66
X	56-3879(F)	2747	3/66
Z	56-2955(D)	2607	5/66
Z	55-3552(D)	2044	5/66
Z	56-3072(D)	2374	5/66
Z	56-3084(D)	2564	5/66
Z	56-3093(D)	2404	5/66
Z	56-3818(F)	2258	5/66
Z	56-3456(D)		
Z	56-3038(D)		
Z	56-3065(D)		
	Lakenheath AFB		
Z	55-2809(D)	2262	5/66
Z	55-2814(D)	2157	5/66
Z	55-2817(D)	1708	5/66
Z	55-2826(D)	1996	5/66
Z	55-2803(D)	2440	5/66
Z	55-2842(D)	2270	5/66
Z	55-2852(D)	2131	5/66
Z	56-3203(D)	1985	5/66
Z	56-3214(D)	2250	5/66
Z	56-3231(D)	2422	5/66
Z	56-3315(D)	2276	5/66
Z	56-3425(d)	2412	5/66

Code	Tail No.	Hours[1]	Date
	Homestead AFB		
X	55-2884(D)	2591	4/66
X	56-3118(D)	unavail.	5/66
X	56-3132(D)	2508	4/66
X	56-3133(D)	2567	4/66
Z	56-2959(D)	2600	4/66
Z	56-3009(D)	2551	4/66
Z	56-3119(D)	2583	4/66
Z	56-3120(D)	2690	4/66
Z	56-3121(D)	2497	4/66
Z	56-3172(D)	2677	4/66
Z	56-3436(D)	2478	4/66
Z	56-2949(D)		
Z	56-3451(D)		
Z	56-2907(D)		
Z	56-3392(D)		
	Nellis AFB		
Zt	55-3506(D)	2057	4/66
Zt	55-3507(D)	2149	4/66
Zt	55-3520(D)	2317	4/66
Zt	55-3708(D)	2235	4/66
Zt	55-3759(D)	2267	4/66
Zt	55-3776(D)	2517	4/66
Zt	55-3561(D)	2270	4/66
Zt	55-3582(D)	2321	4/66
Zt	56-3924(F)	2009	4/66
Z	56-3110(D)		
	Wethersfield AFB		
Z	55-3616(D)	2201	5/66
Z	55-3644(D)	2484	5/66
Z	55-3663(D)	2314	5/66
Z	55-3665(D)	2501	5/66
Z	55-3679(D)	2393	5/66
Z	55-3683(D)	2440	5/66
Z	55-3690(D)	2312	5/66
Z	56-2964(D)	2867	5/66
Z	56-2983(D)	2386	5/66
Z	56-3001(D)	2199	5/66
Z	56-3402(D)	2113	5/66
Z	56-3434(D)	2423	5/66

(Continued)

TABLE XV. (Concluded)

Code	Tail No.	Hours[1]	Date
	England AFB		
X	56-2344(D)	2754	3/66
X	56-2989(D)	2710	3/66
X	56-3152(D)	2506	3/66
X	56-3365(D)	2489	3/66
Z	55-3557(D)	2112	4/66
Z	55-2793(D)	2033	4/66
Z	55-2860(D)	2801	4/66
Z	55-2912(D)	2318	4/66
Z	55-2919(D)	2362	4/66
Z	55-2923(D)	2568	4/66
Z	55-2929(D)	2364	4/66
Z	56-2952(D)	2465	4/66
Z	56-2956(D)	2535	4/66
Z	55-3704(D)	2488	4/66
Z	55-3709(D)	2707	4/66
Z	55-3741(D)	2126	4/66
Z	55-3739(D)	2341	4/66
Z	55-3757(D)	2169	4/66
Z	55-3774(D)	2541	4/66
Z	55-3797(D)	2729	4/66
Z	56-[illegible]087(D)	2669	4/66
Z	56-3167(D)	2143	4/66
Z	56-3173(D)	2546	4/66
Z	56-2927(D)		
Z	55-2874(D)		

Code	Tail No.	Hours[1]	Date
	Myrtle Beach AFB		
X	55-3661(D)	2709	3/66
X	56-3383(D)	2736	3/66
X	56-3420(D)	2749	3/66
X	55-3770(D)	2808	3/66
Z	55-[illegible]877(D)	2296	4/66
Z	55-2900(D)	2138	4/66
Z	55-2949(D)	2345	4/66
Z	56-3357(D)	2456	4/66
Z	56-3356(D)	2484	4/66
Z	56-3360(D)	2418	4/66
Z	56-3372(D)	2240	4/66
Z	56-3379(D)	2557	4/66
Z	56-3381(D)	2504	4/66
Z	56-3384(D)	2541	4/66
Z	56-3385(D)	2319	4/66
Z	56-3413(D)	2502	4/66
Z	56-3415(D)	2415	4/66
Z	56-3435(D)	2382	4/66
Z	56-3459(D)	2272	4/66
Z	56-3462(D)	2543	4/66
Z	56-3071(D)	2409	4/66
Z	56-3073(D)	2447	4/66

[1] Airplane hours when instrumented

LEGEND

X = X-Ray A/P
Y = Yankee A/P
Z = Zulu A/P
Zt = Zulu (Thunderbird) A/P
(D)= F-100D
(F)= F-100F

F-100 STRUCTURAL INTEGRITY PROGRAM - PILOT'S AND CREW CHIEF'S LOG
F-100D and F-100F Airplanes Changed by T. O. 1F-100-974

1. Date	2. Organization	3. Location	4. Aircraft model, Serial Number F-100( )
5. Pilot			6. Total Aircraft Hours
7. Gross Weight Take-off ______ Landing ______	8. In-flight Refueling Number of hookups ______ Total weight of fuel added ______	9. Landings Number of landings ______	Before Flight This Flight After Flight

10. Mission: Check the items that most nearly describe the mission flown. In all instances at least one item must be checked; however, no more than three items will be checked to describe any one mission. If mission is not described on this list, write type of mission flown in space provided.

a. Administrative or Ferry		e. Flight Test		i. Ground Attack - Low-angle	
b. Formation or Transition		f. Air-to-air Tactics		j. Ground Attack - High-angle	
c. Reconnaissance or ECM		g. Low-altitude		k.	
d. Tow-target		h. "Pop-up" Bombing		l.	

11. Remarks:

INSTRUCTIONS

PILOT in command will: a. Complete blocks 5 through 11. b. Enter "Remarks" when in the pilot's judgment the airplane has been exposed to unusual or excessive operations, such as hard landings, taxi runs at high speeds, extremely rough weather, etc, or if intermediate refueling stops were made during the flight.
CREW CHIEF will: a. Place a copy of this work sheet with Form 781 on assigned aircraft to which it is applicable.
b. Make entries in blocks 1 through 4; also enter "Before flight" hours from Form 781 in block 6. c. Ensure completion of blocks 12, 14 and 15 on Sheet 2.
d. Upon completion of this Work Sheet, it will be returned to Maintenance Officer.
MAINTENANCE OFFICER will: Ensure maintenance of this sheet and forward one week's accumulated Work Sheets to F-100 Project Engineering, North American Aviation, Inc., Los Angeles International Airport, Los Angeles, California 90009.

Sample Work Sheet 1F-100-9WS-1 (Sheet 1 of 2)

FIGURE 62. F-100 STRUCTURAL INTEGRITY PROGRAM - PILOT'S AND CREW CHIEF'S LOG

STATISTICAL ACCELEROMETER (G LEVEL COUNTER) READINGS AND AIRCRAFT LOADING CHART

(Refer to T. O. 1F-100-9)

12. Crew Chief	13. Armorer

14. Counter readings

STATISTICAL ACCELEROMETER PANEL

"G" Peak Level Counters

(At centerline on forward bulkhead main wheel wells)

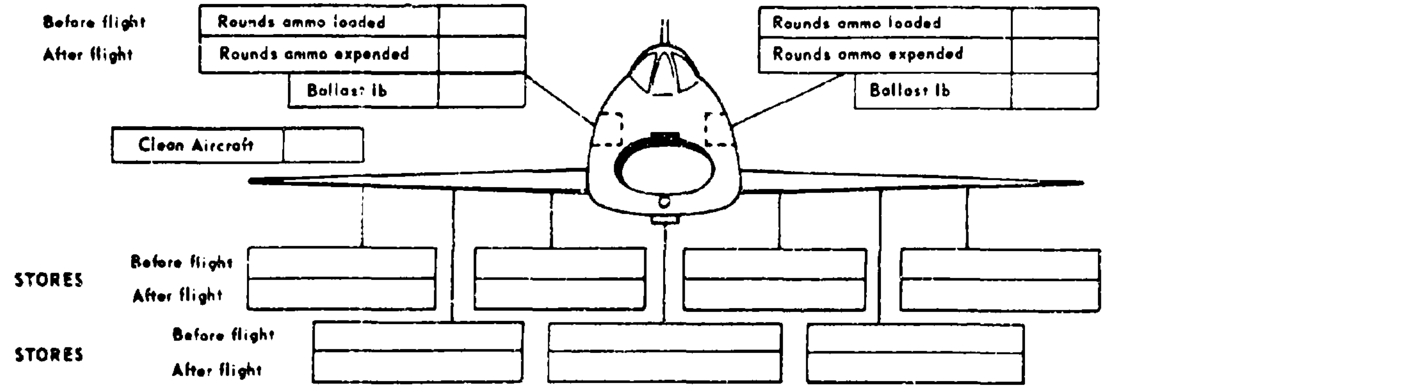
Before flight / After flight	-2 G		
Before flight / After Flight	-1 G	0. G	+2 G
Before Flight / After flight	+3 G	+4 G	+5 G
Before Flight / After flight	+6 G	+7 G	+8 G

INSTRUCTIONS

CREW CHIEF will: a. Record G-level counter readings before and after each flight.
(1) Open right wheel door. (Refer to "F-100 Hydraulically Operated Systems," T. O. 1F-100D(I) or F(I)-2-4.)
(2) Enter G-level readings in block 14. b. Enter quantity of fuel (gallons) at each external store in block 15. c. Make entries showing after flight quantities.
ARMORER will: a. Enter first initial, name and rank in block 13. b. Indicate type and quantity of stores at each station where shown in block 15. c. Indicate after-flight condition, and quantities. If store is empty, insert "E." If dropped or jettisoned, insert "D."

15. Loading data.

AIRCRAFT LOADING CHART



Sample Work Sheet 1F-100-9WS-1 (Sheet 2 of 2)

FIGURE 62 (Concluded)

TABLE XVI

F-100 AIRCRAFT STRUCTURAL INTEGRITY PROGRAM AIRPLANES
DEPLOYED TO VIETNAM WAR BASES
(Flight and combat hours for period 1 September 1966 to 28 February 1967)

Code	Tail No.	Flights	Combat④ Hours	Hours of Data	Last Flt. Date	Remarks
Z①	55-2793	32	102.2	51.7	24 Nov 66	
Z	55-2860	30	129.1	41.1	19 Dec 66	
Z	55-2877	42	168.3	73.9	17 Nov 66	S.A. Malf.③
Z	55-2884	11	38.6	24.5	8 Oct 66	Homestead AFB
Z	55-2900	45	253.8	72.7	31 Jan 67	
Z	55-2912	49	134.8	74.5	30 Nov 66	Lost 3-20-67
Z	55-2914	9	28.9	15.9	22 Nov 66	
Z	55-2923	39	94.2	62.3	15 Nov 66	S.A. Malf.
Z	55-2929	27	88.5	42.6	14 Nov 66	S.A. Malf.
Z	55-2949	40	250.1	68.6	1 Feb 67	S.A. Malf.
Z	55-3557	35	73.4	65.6	24 Nov 66	S.A. Malf.
X②	55-3661	26	114.0	42.4	20 Jan 67	S.A. Malf. (Last 2 Flights)
Z	55-3704	29	146.0	48.3	25 Nov 66	
Z	55-3709	37	166.9	60.5	26 Nov 66	
Z	55-3741	4	23.3	12.6	31 Oct 66	
Z	55-3757	37	146.3	59.7	27 Nov 66	S.A. Malf.
Z	55-3774	34	110.0	52.9	12 Jan 67	
Z	55-3797	5	6.4	6.4	19 Sep 66	S.A. Malf.
Z	56-2907					Lost 12-15-66
Z	56-2927	26	153.9	49.6	22 Nov 66	
X	56-2944	5	24.8	7.6	1 Oct 66	Uncertain
Z	56-2952	21	39.5	26.7	2 Nov 66	S.A. Malf.
Z	56-2956				8 Jul 66	Lost 9-27-66
X	56-2989	38	153.8	68.3	13 Dec 66	
Z	56-3071	17	26.1	26.1	12 Sep 66	Lost 9-13-66
Z	56-3073	81	168.1	121.5	1 Dec 66	S.A. Malf.
Z	56-3087	40	102.6	66.5	24 Nov 66	
X	56-3152	2	4.5	2.8	8 Sep 66	
Z	56-3167	7	12.7	12.7	19 Oct 66	Lost 10-26-66
Z	56-3173	39	132.9	60.4	24 Nov 66	
X	56-3365	20	120.9	25.6	10 Dec 66	
Z	56-3372	11	116.5	16.8	30 Oct 66	S.A. Malf.
Z	56-3379	69	152.4	107.8	19 Dec 66	
Z	56-3381	20	115.6	37.6	4 Nov 66	
X	56-3383	85	177.7	124.6	28 Jan 67	S.A. Malf.
Z	56-3384	2	109.1	44.4	24 Oct 66	S.A. Malf.
Z	56-3385	12	26.5	18.8	8 Nov 66	
Z	56-3413	145	263.1	216.7	31 Jan 67	S.A. Malf.
Z	56-3415	43	211.7	67.5	26 Jan 67	S.A. Malf.
Z	56-3435	44	124.7	68.2	31 Oct 66	S.A. Malf.
Z	56-3462	6	83.3	9.4	26 Nov 66	
Z	56-3739					Lost 7-21-66
Z	56-2949	28	64.3	49.6	7 Dec 66	
Total Flights		1292				

① Z - Zulu A/P ② X - X-ray A/P ③ Statistical Accelerometer Malfunction
④ F-100 Vietnam combat usage is averaging 55 hours per month per airplane

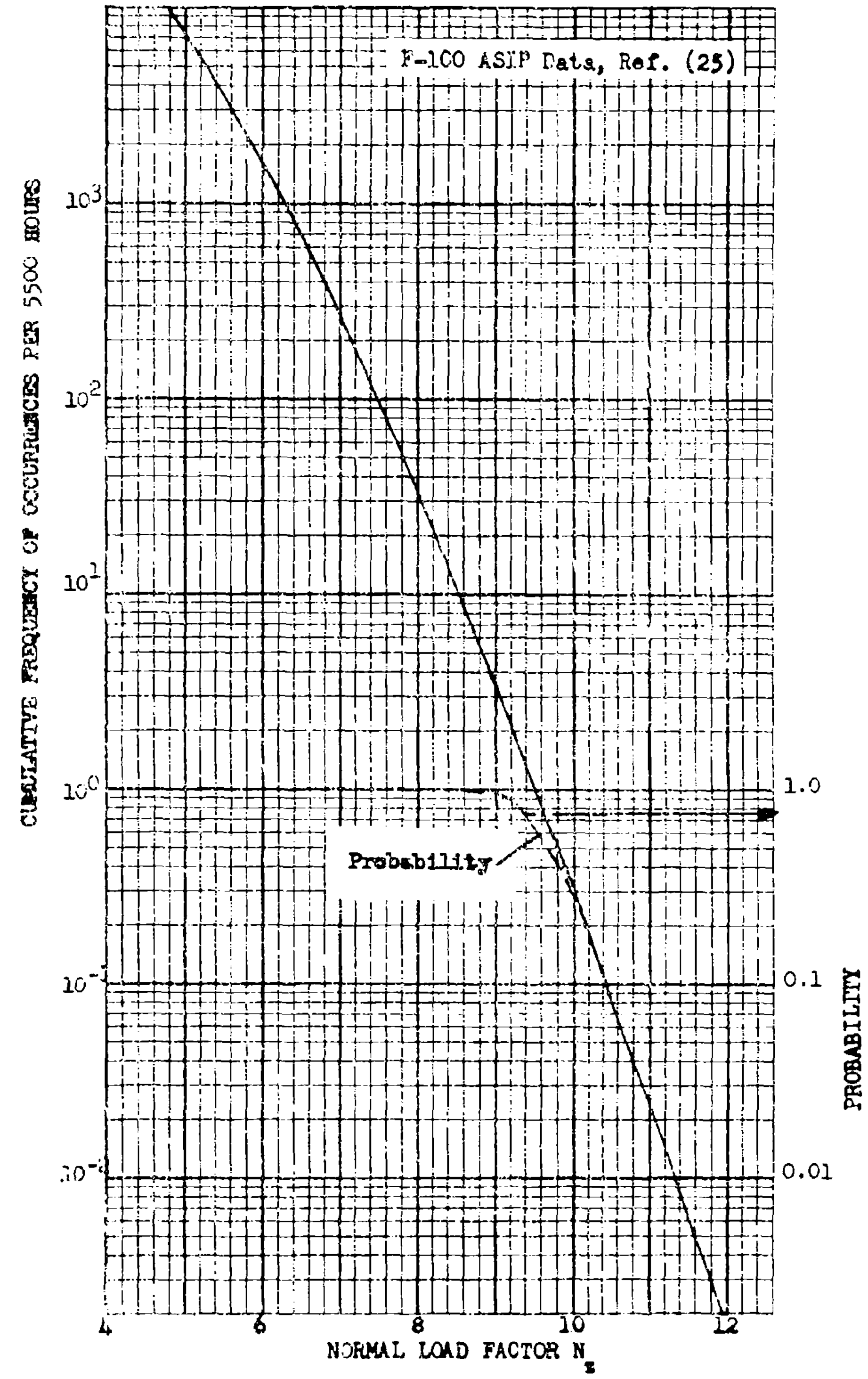


FIGURE 63. F-100 ASIP PHASE I NORMAL LOAD FACTOR SPECTRUM

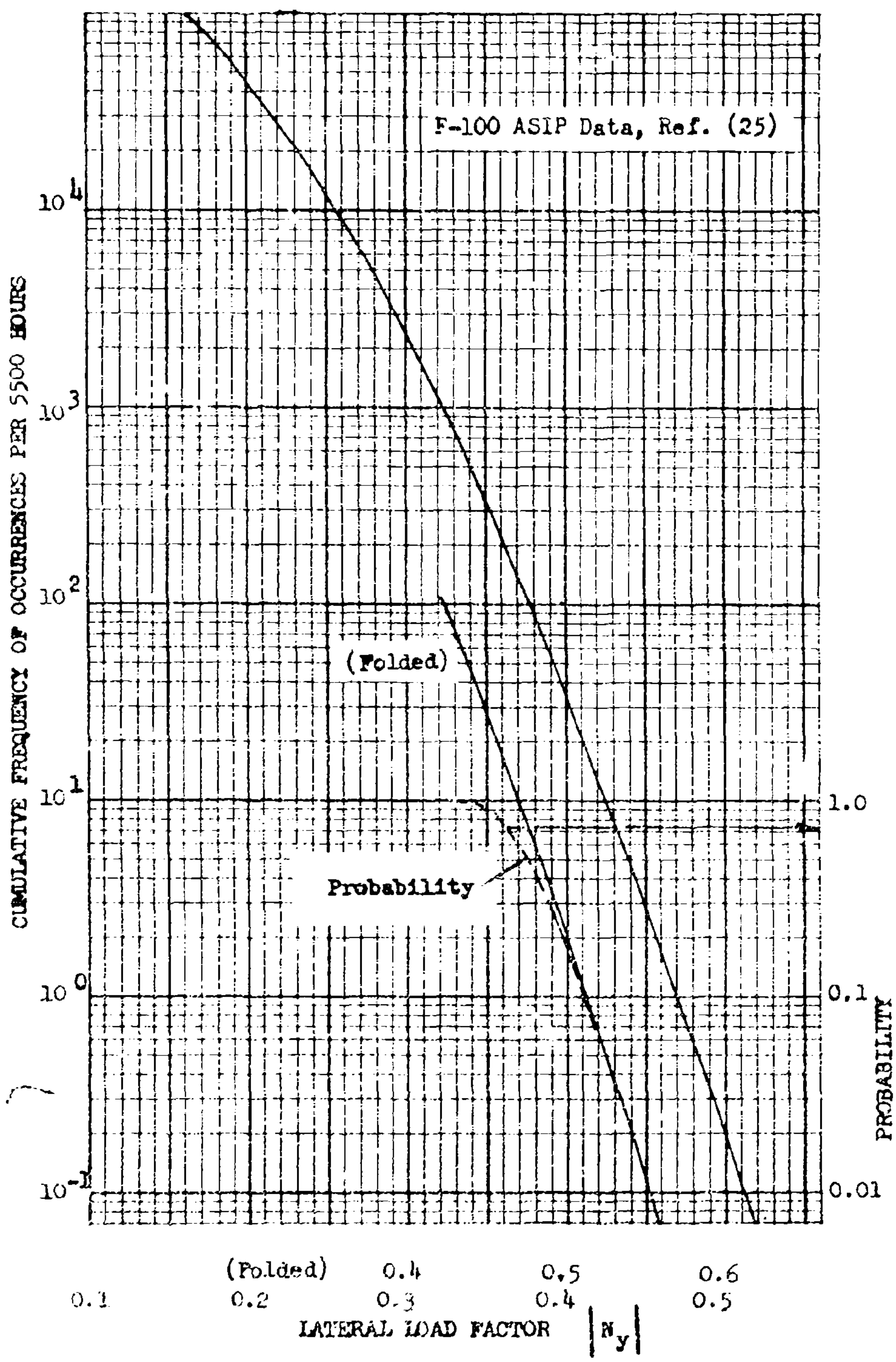


FIGURE 64. F-100 ASIP PHASE I LATERAL LOAD FACTOR SPECTRUM

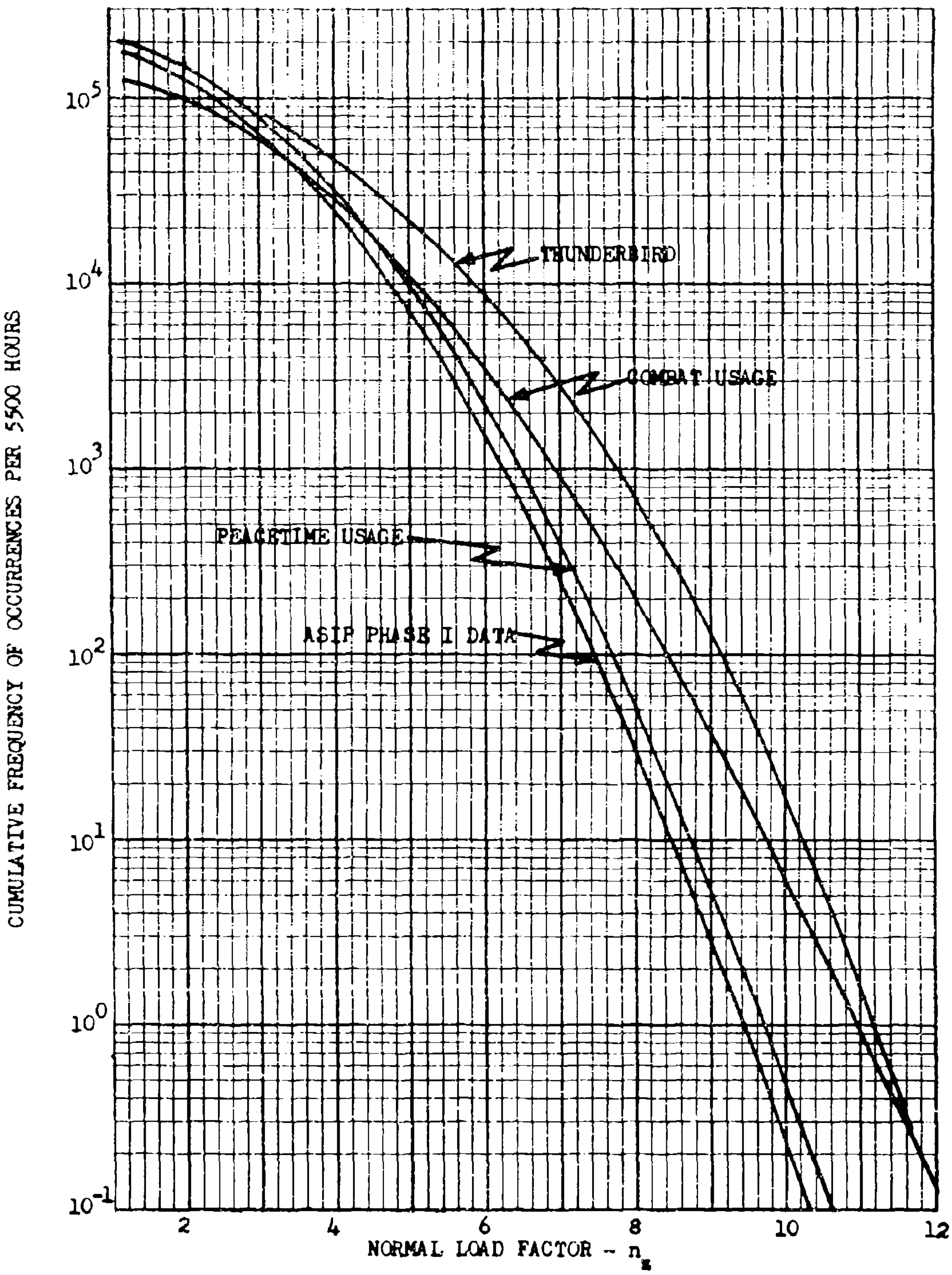


FIGURE 65. LOAD FACTOR SPECTRUM COMPARISON

The reason for this is that the "Thunderbirds" are based at Nellis and these data are considered demonstrational and not representative of normal service operation. The Thunderbird data have been added to Figure 65 for comparison.

A least squares method was used to fit the raw data to a truncated distribution curve of the form:

$$Y = ae^{-\left(\frac{X^2}{K^2}\right)} \qquad (2 < x < \infty)$$

where Y = load factor exceedances

X = load factor

a,k = constants

This procedure provides a means of fitting a smooth curve to each spectrum and provides a mathematical description of areas of the spectrum where sample data size does not provide a good description.

The data for the various missions were classified into the categories of Air-to-Air Gunnery, High Angle Bombing and Low Angle Bombing. The spectra for these categories are shown on Figure 66. They can be compared with the composite spectra on Figure 65. Only the composite spectra are used in the analyses presented in this report although it would be necessary to synthesize the spectrum from data on the various categories when predicting a spectrum for initial design.

c. F-100 Loads Correlation

A flight loads survey [28] was performed to obtain loads at the design limit conditions. A matrix of altitudes and Mach numbers were flown at the design limit load factors to search out the critical loading conditions. The results of this program showed that the maximum measured wing loads exceeded the design calculated critical condition by six percent. The maximum measured horizontal tail loads were only 75 percent of the critical design value. The maximum measured vertical tail loads occurred during rolling pullout maneuvers, but they turned out to be two percent less than the design load value from a rudder kick condition. Other structural demonstration programs and specialized engineering flight tests for store loads and ejections, where selected airframe components and surfaces were instrumented with tip targets and calibrated strain gages tended to confirm these findings.

The Aircraft Structural Integrity Program,[25] wherein the airplanes were instrumented with bending moment strain gages and flown at twice the normal usage rate, showed that the major mission profiles were subsonic at low altitudes (10 to 15,000 feet) and with external stores. As such, these conditions were all less than the critical design and/or measured values. However, the same trends appear with respect to relative load levels. The wing loads, although less than design, were more closely allied with the normal load factors at levels below the design limit value. At limit load factor, and above, the wing bending moment trend with load factor drops off because of the inboard movement of the center of pressure at high angles of attack. These trends are illustrated graphically on the percent of limit spectrum, Figure 67. The

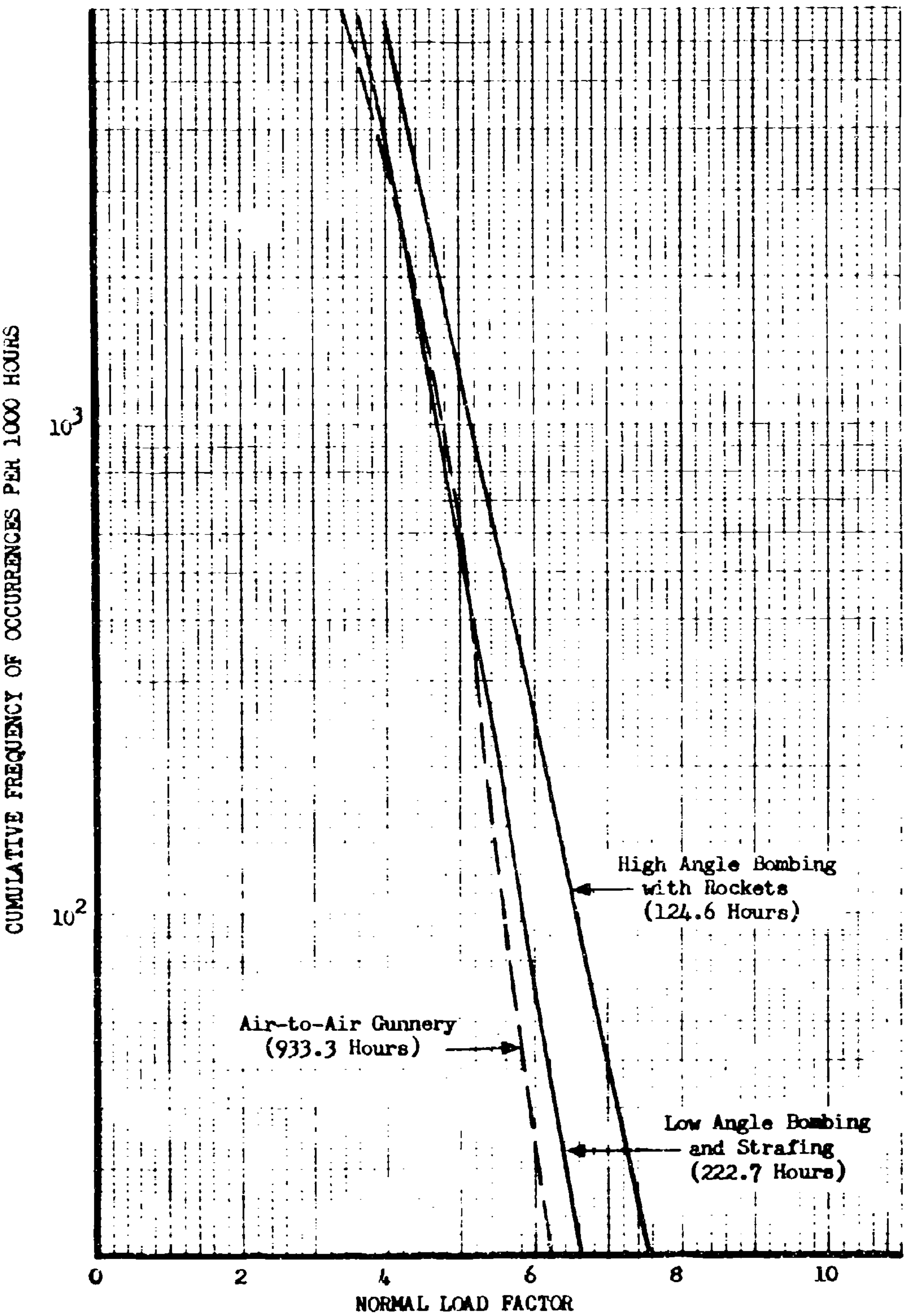


FIGURE 66. F-100 SPECTRA COMPARISON

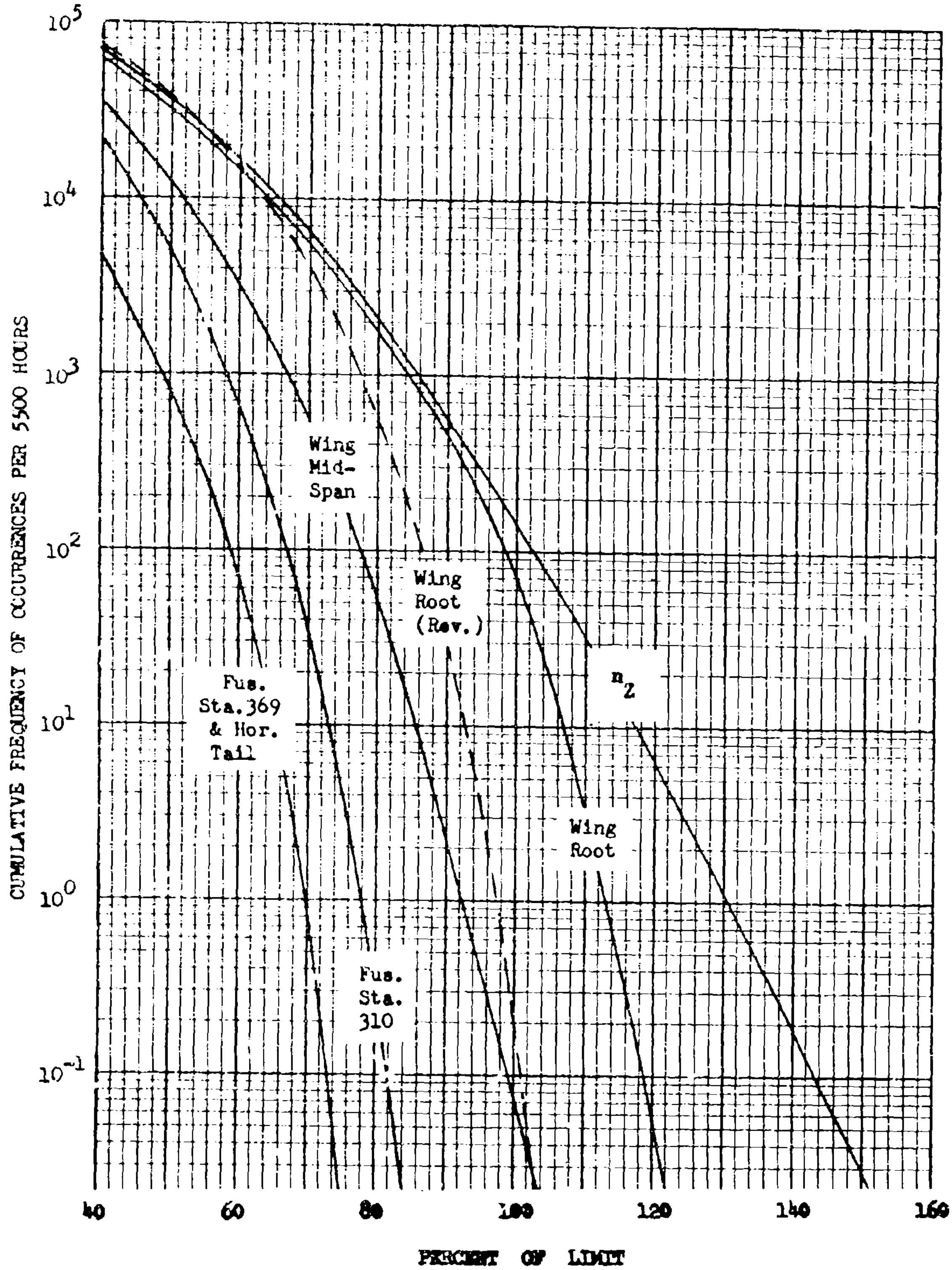


FIGURE 67. F-100 ASIP LIMIT VALUES-NORMAL (SYMMETRIC)

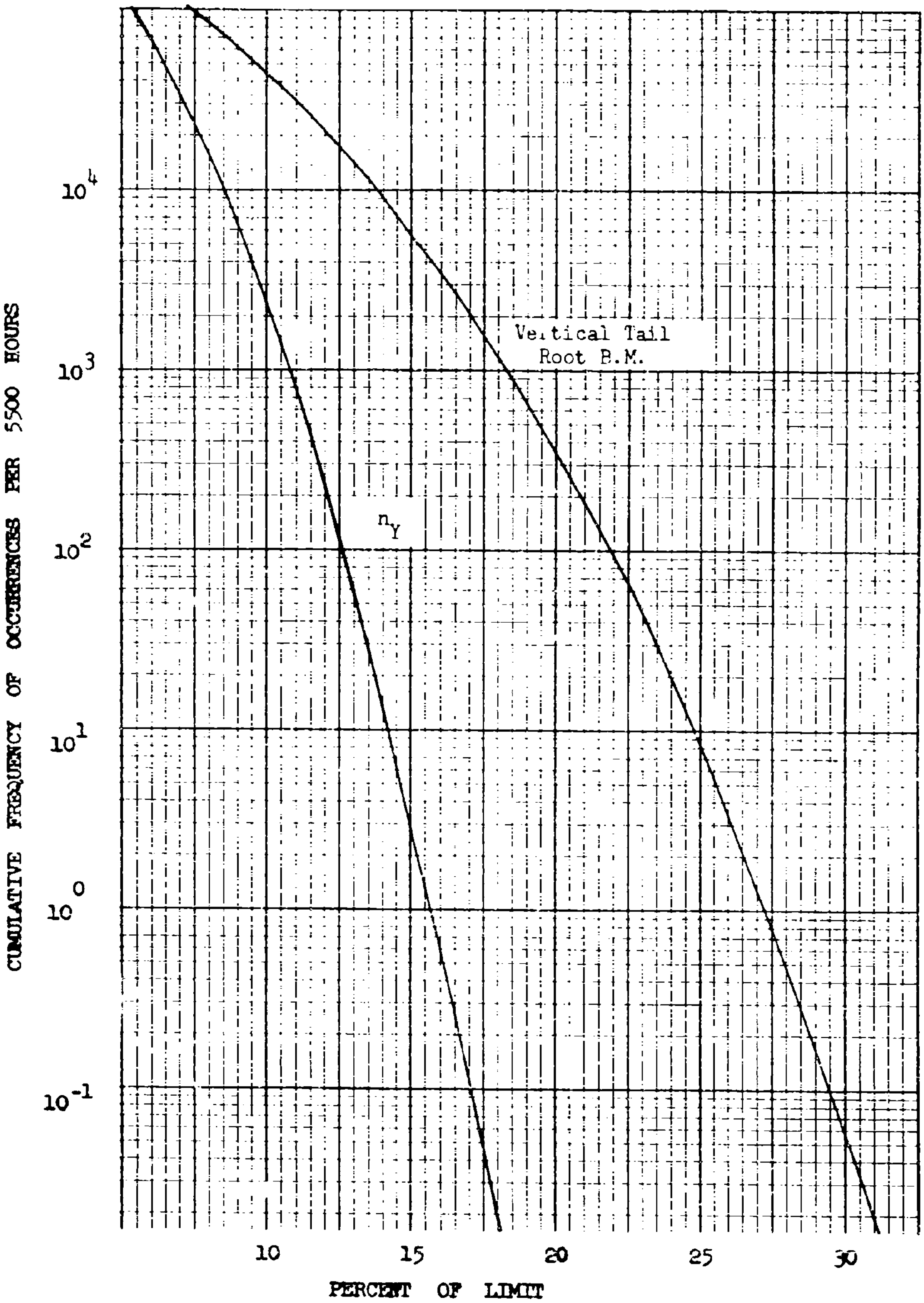


FIGURE 68. F-100 ASIP LIMIT VALUES-
LATERAL (ASYMMETRIC)

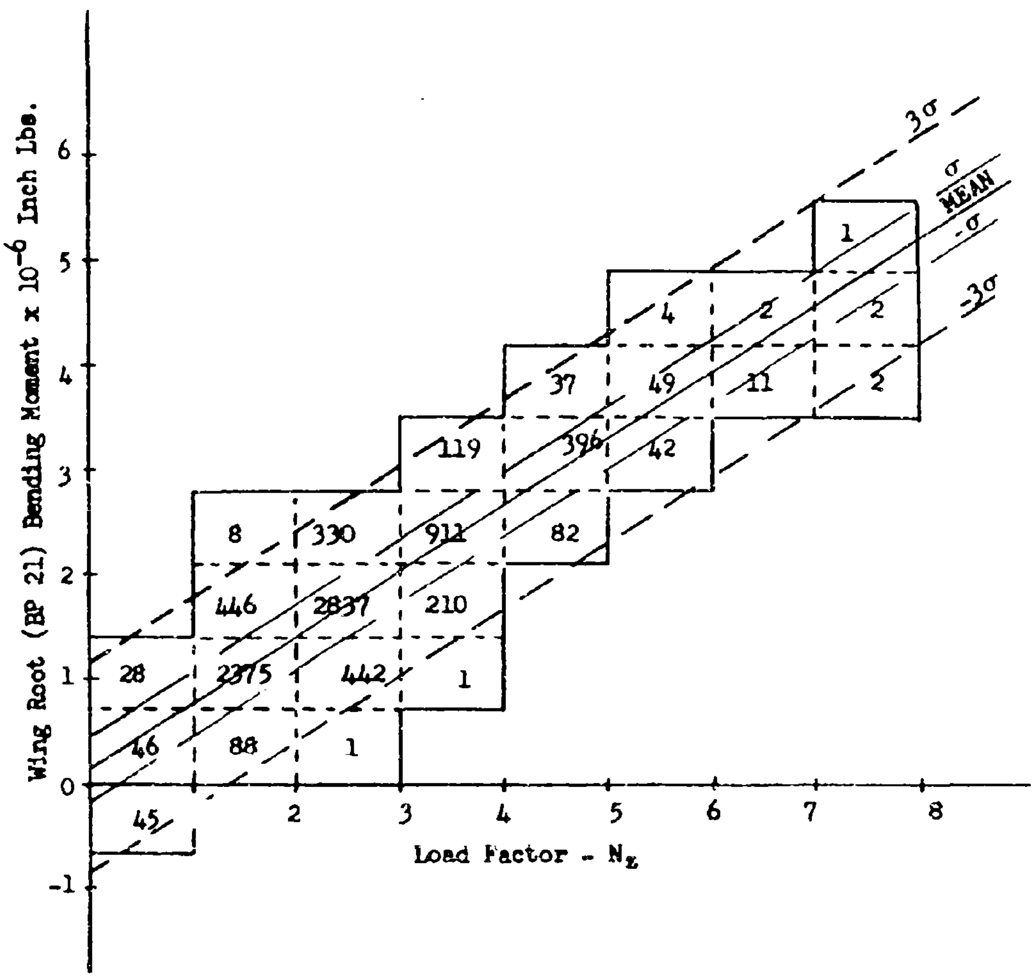


FIGURE 69. BENDING MOMENT - LOAD FACTOR CORRELATION

vertical tail loads from operational usage in comparison to design strength, Figure 68, are so low as to be in the noise level. The horizontal tail loads as reflected in the fuselage moments are also well below design strength values, Figure 67.

A graphical illustration of the correlation of the wing root bending moment with airplane c.g. load factor is shown on Figure 69. The calculated least squares solution for mean line and standard error dispersion lines is shown. It is assumed that the data in each load factor level are normally distributed. The 3σ lines define boundaries which contain 99.7 percent of the data for large samples. This definition of dispersion is considered adequate for the extreme values of load factor. Bending moment occurrences in each load factor interval are established for the total number of load factor occurrences in that interval as obtained from the extrapolated 5500 hour load factor spectrum. Summing these occurrences for each bending moment interval defines the frequency distribution of the largest to the smallest bending moments for the loading spectra. Tabulated data for the correlation are presented in Table XVII for data obtained from the Phase I ASIP program. Comparable data from combat and peacetime usage are given on Tables XVIII and XIX.

d. F-100 Bending Moment Spectra

Bending moment spectra for two wing stations, two fuselage stations, and the vertical tail root are shown in Figures 70 through 74. These are taken from the flight measured loads on lifting surfaces from normal service operations. The Phase III laboratory fatigue tests were conducted to the loading spectra defined by Figure 70 for the wing root. A failure was experienced during the tests to the "fitted" correlation which was conservative. The tests have been resumed but a revised correlation is used, Figure 75, which is a more realistic representation of the latest ASIP loads data.

A histogram representing the frequency of occurrence of wing root bending moments is presented on Figure 76. These data are for the 3308 flight hours recorded in the Phase I program, correlated from 113.4 hours of good strain gage readings taken from Yankee #2, Figure 69. The data are converted to a spectrum and probability curve on Figure 70. The data are further converted into spectra defined in terms of percent of limit load on Figure 77. Corresponding histograms and spectra for the wing midspan bending moments are shown on Figures 78 and 71.

Fuselage bending moment data at Stations 310 and 369 are shown on Figures 79, 72, 80, and 73, respectively. A histogram for vertical tail root bending moment is given on Figure 81. The corresponding spectrum and probability curves are presented in Figure 74.

e. Comparison of Spectra for Loads and Load Factors

The plot of normal load factor and loads at four stations on the airplane versus percent of design limit load, Figure 67, is a significant comparison. This puts the usage loads in perspective with the normal load factor. While it is true that the normal load factor spectrum is severe, the accompanying loads are relatively low in comparison to design limit strength values. There are two reasons for this. First the usage spectra is primarily at subsonic

TABLE XVII

WING ROOT BENDING CORRELATION WITH LOAD FACTOR (PHASE I)

BM Int $\times 10^{-6}$ in-lbs	% of Cond. Used	N_Z Interval 2.0–3.0	3.0–4.0	4.0–5.0	5.0–6.0	6.0–7.0	7.0–8.0	8.0–9.0	9.0–10.0	Tot. Occur. for each BM Int.	Σ Occur
5.6–5.9	1.34–1.41										
5.3–5.6	1.27–1.34										
5.0–5.3	1.20–1.27					1	1			2	2
4.7–5.0	1.129–1.20				2	10	11	3	1	27	29
4.4–4.7	1.052–1.129				28	83	44	9	1	165	194
4.1–4.4	.985–1.052				250	287	81	11	1	630	824
3.8–4.1	.913–.985			189	1015	487	71	8		1770	2594
3.5–3.8	.840–.913			1292	1895	376	31	1		3595	6189
3.2–3.5	.768–.840		291	4267	1675	136	5			6374	12563
2.9–3.2	.697–.768		2216	6552	710	28	1			9507	22070
2.6–2.9	.624–.697	336	8145	4677	125	2				13285	35355
2.3–2.6	.552–.624	2863	13896	1552	10					18321	53676
2.0–2.3	.480–.552	11699	11019	251						22969	76645
1.7–2.0	.408–.480	22178	4068							26246	102891
1.4–1.7	.336–.408	19538	679							20217	123108
1.1–1.4	.264–.336	7994	56							8050	131158
.8–1.1	.192–.264	1514								136	132808
.5–.8	.120–.192	136									
.2–.5											
No. in Interval – N_Z		66258	40370	18780	5710	1410	245	32	3		
Cumulative Occur.		132808	66570	26180	7400	1690	280	35	3		

TABLE XVIII

WING ROOT BENDING CORRELATION WITH LOAD FACTOR (COMBAT USAGE)

BM Int x 10^{-6} in-lbs	% of Cond. Used	Load Factor Interval								Tot. Occur. for each BM Int.	Σ Occur
		2.0-3.0	3.0-4.0	4.0-5.0	5.0-6.0	6.0-7.0	7.0-8.0	8.0-9.0	9.0-10.0		
5.6-5.9	1.34-1.41										
5.3-5.6	1.27-1.34										
5.0-5.3	1.20-1.27					1	4	2	1	8	8
4.7-5.0	1.129-1.20				2	19	30	14	5	70	78
4.4-4.7	1.052-1.12				37	153	129	41	10	370	448
4.1-4.4	.985-1.05				326	528	239	53	12	1158	1606
3.8-4.1	.913-.985			171	1330	896	205	31	7	2640	4246
3.5-3.8	.840-.913			1170	2491	690	91	8	2	4452	8608
3.2-3.5	.768-.840		216	3865	2195	253	15	1		6546	15244
2.9-3.2	.697-.768		1646	5936	920	42	1			8545	23789
2.6-2.9	.624-.697	201	6051	4237	163	3				10655	34444
2.3-2.6	.552-.624	1711	10325	1406	16					13458	47902
2.0-2.3	.480-.552	6992	8186	227						15405	63307
1.7-2.0	.408-.480	13255	3022							16277	79584
1.4-1.7	.336-.408	11677	504							12181	91765
1.1-1.4	.264-.336	4778	42							4820	96585
.8-1.1	.192-.264	905								905	97490
.5- .8	.120-.192	81								81	97571
.2- .5											
No. in Interval		39600	29992	17012	7480	2585	715	150	37		
Cumulative Occur.		97571	57971	27979	10967	3487	902	187	37		

TABLE XIX

WING ROOT BENDING MOMENT CORRELATION WITH LOAD FACTOR (PEACETIME USAGE)

BM Int x 10^{-6} in-lbs	% of Cond. Used	Load Factor Interval								Tot. Occur. for each BM Int.	Σ Occur
		2.0-3.0	3.0-4.0	4.0-5.0	5.0-6.0	6.0-7.0	7.0-8.0	8.0-9.0	9.0-10.0		
5.6-5.9	1.345-1.417										
5.3-5.6	1.273-1.345					0	0	0	0	0	0
5.0-5.3	1.201-1.273				0	1	1	1	0	3	3
4.7-5.0	1.129-1.201				2	12	13	4	1	32	35
4.4-4.7	1.052-1.129				34	99	55	11	1	200	235
4.1-4.4	.985-1.052			0	300	341	102	15	2	760	995
3.8-4.1	.913- .985			211	1224	580	88	9	1	2113	3108
3.5-3.8	.840- .913		0	1438	2294	447	39	2	0	4220	7328
3.2-3.5	.768- .840		336	4748	2021	163	7	0		7275	14603
2.9-3.2	.697- .768	0	2564	7293	847	27	0			10731	25334
2.6-2.9	.624- .697	371	9423	5204	150	2				15150	40484
2.3-2.6	.552- .624	3144	16072	1726	14	0				20956	61440
2.0-2.3	.480- .552	12852	12744	280	0					25876	87316
1.7-2.0	.408- .480	24360	4707	0						29067	116383
1.4-1.7	.336- .408	21460	784							22244	138627
1.1-1.4	.264- .336	8776	65							8841	147468
.8-1.1	.192- .264	1659	0							1659	149127
.5- .8	.120- .192	153								153	149280
.2- .5		0									
No. in Interval		72775	46695	20900	6886	1672	305	42	5		
Cumulative Occur.		149280	76505	29810	8910	2024	352	47	5		

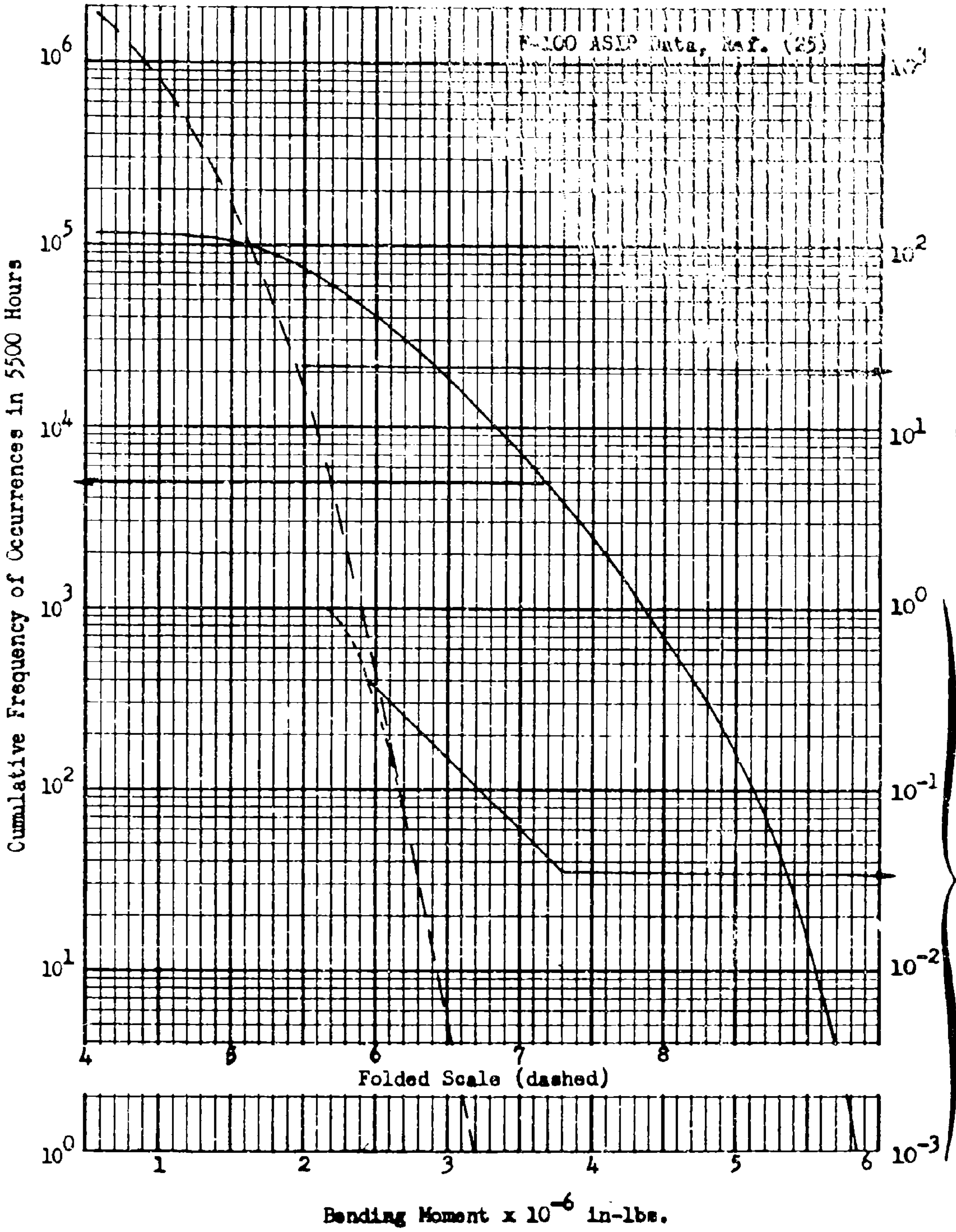


FIGURE 70. F-100 ASIP PHASE I WING ROOT BENDING MOMENT SPECTRUM

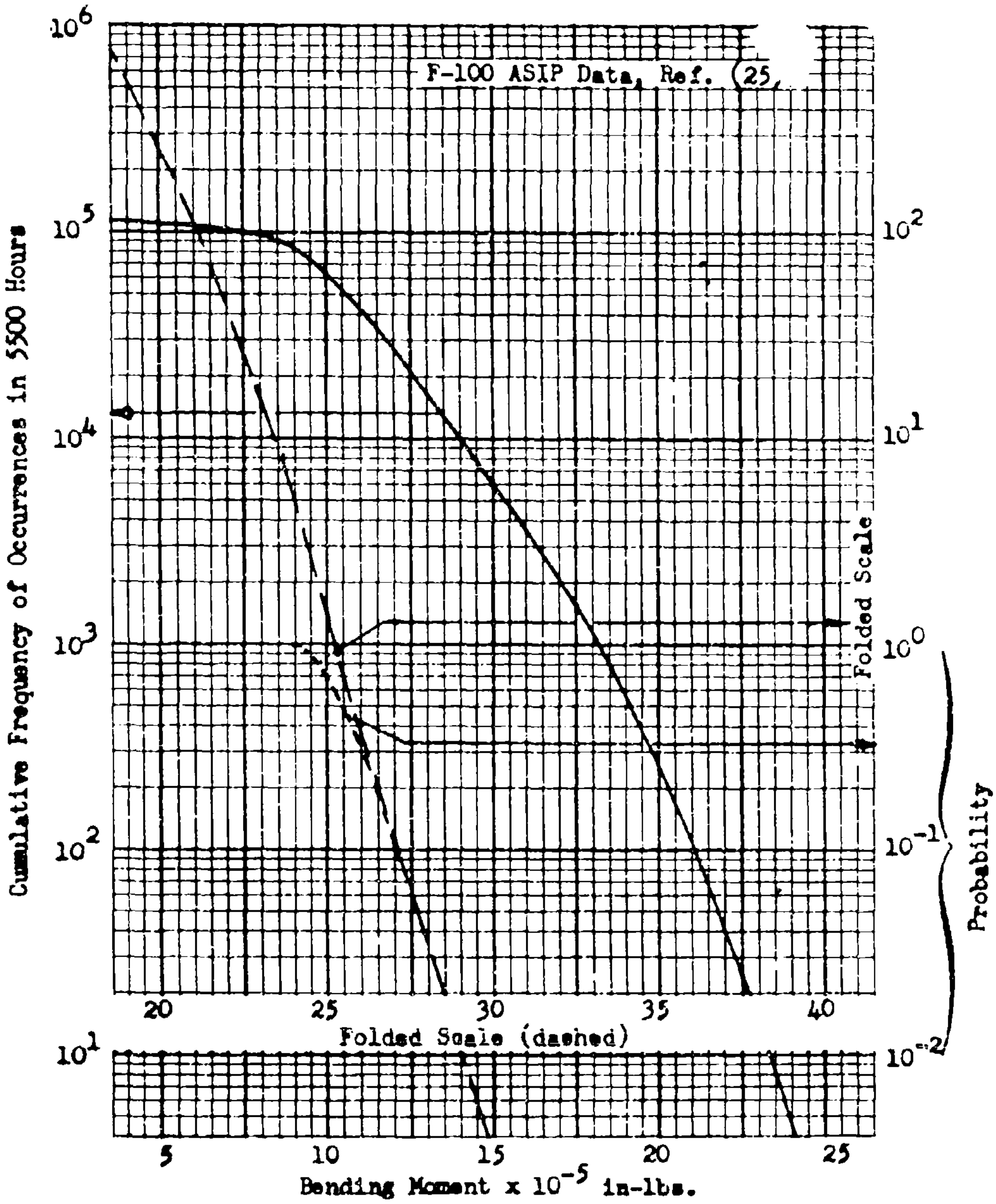


FIGURE 71. F-100 ASIP PHASE I WING MIDSPAN BENDING MOMENT SPECTRUM

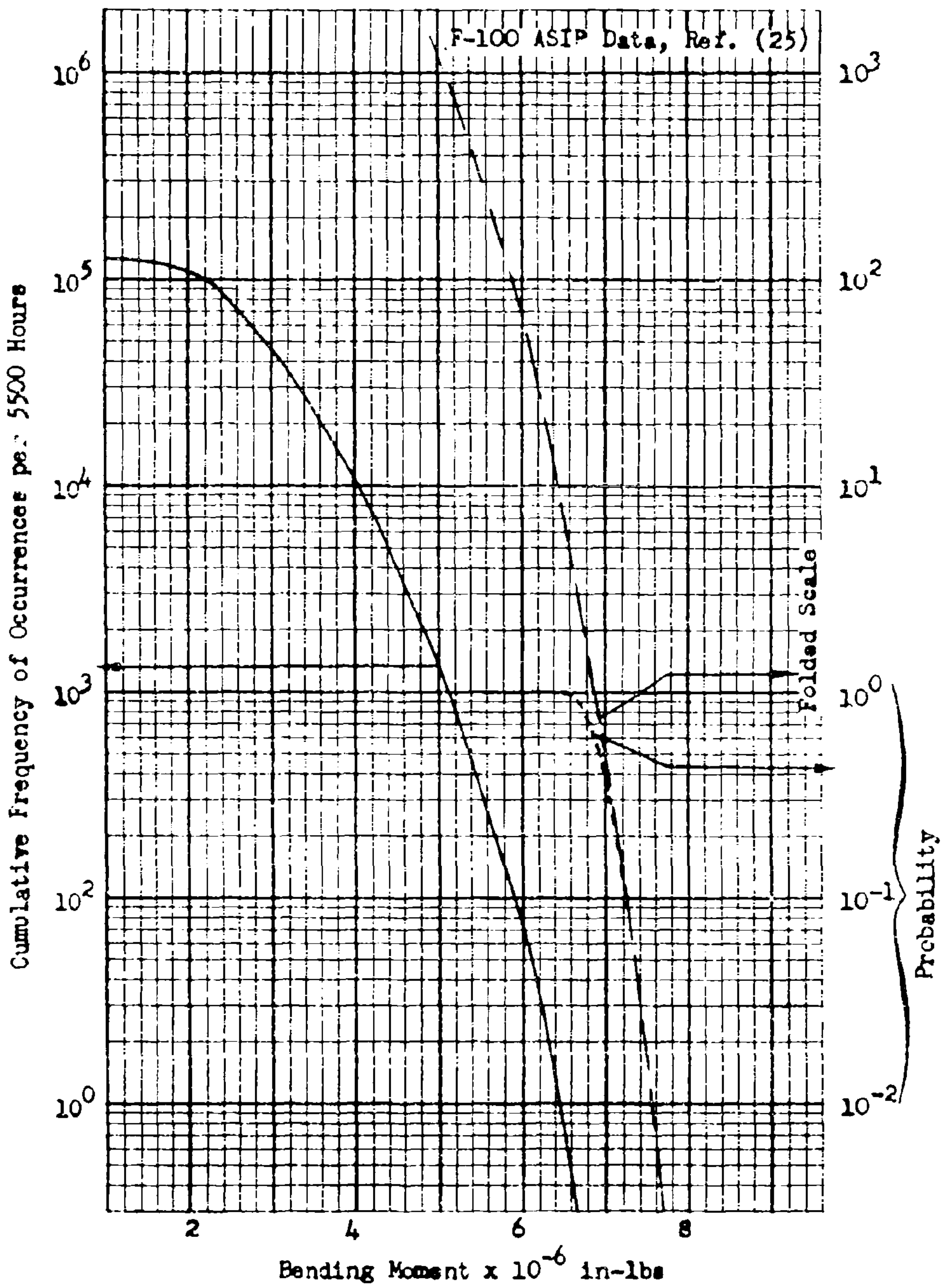


FIGURE 72. F-100 ASIP PHASE I FUSELAGE STATION 310 BENDING MOMENT SPECTRUM

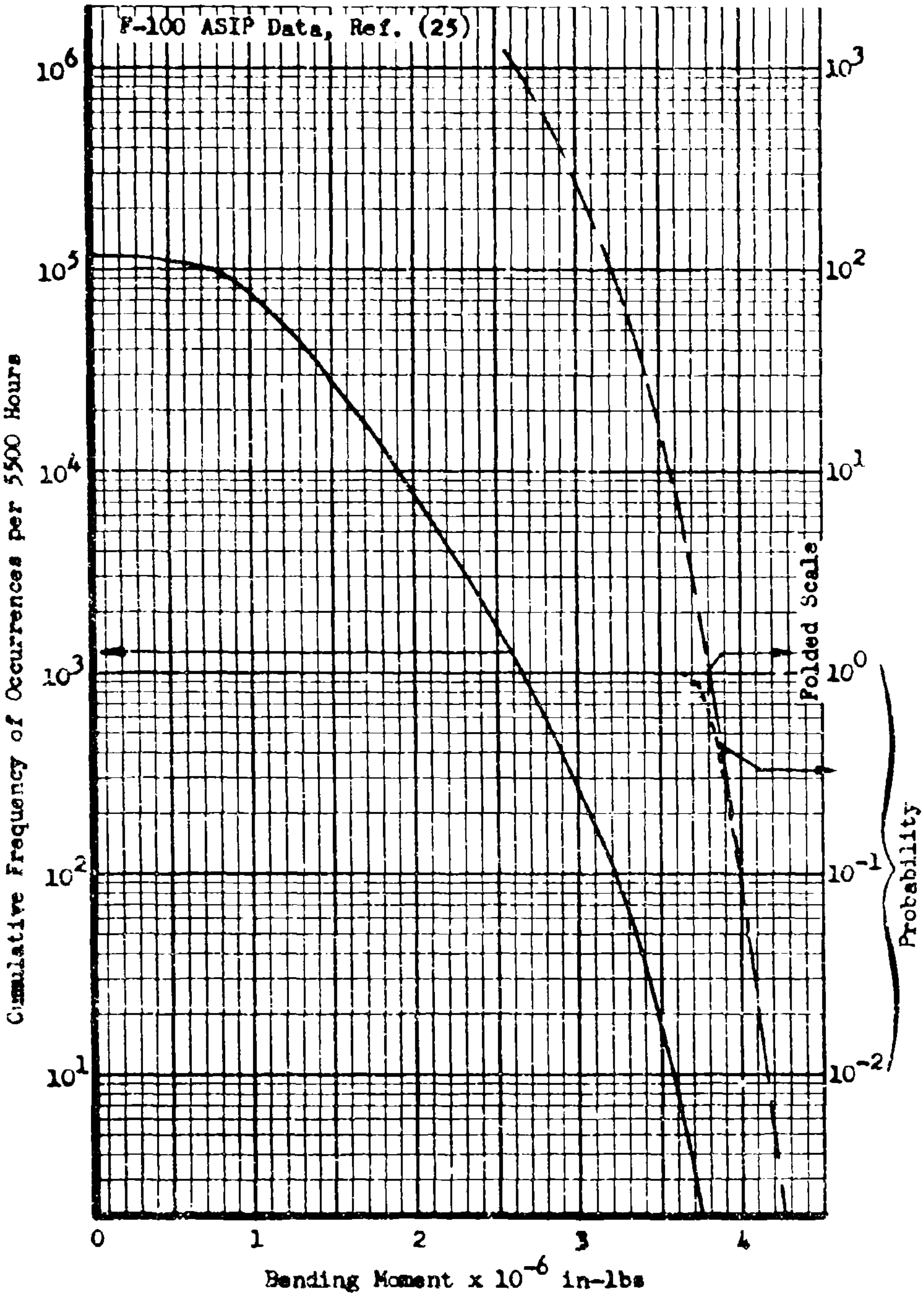


FIGURE 73. F-100 ASIP PHASE I FUSELAGE STATION 369 BENDING MOMENT SPECTRUM

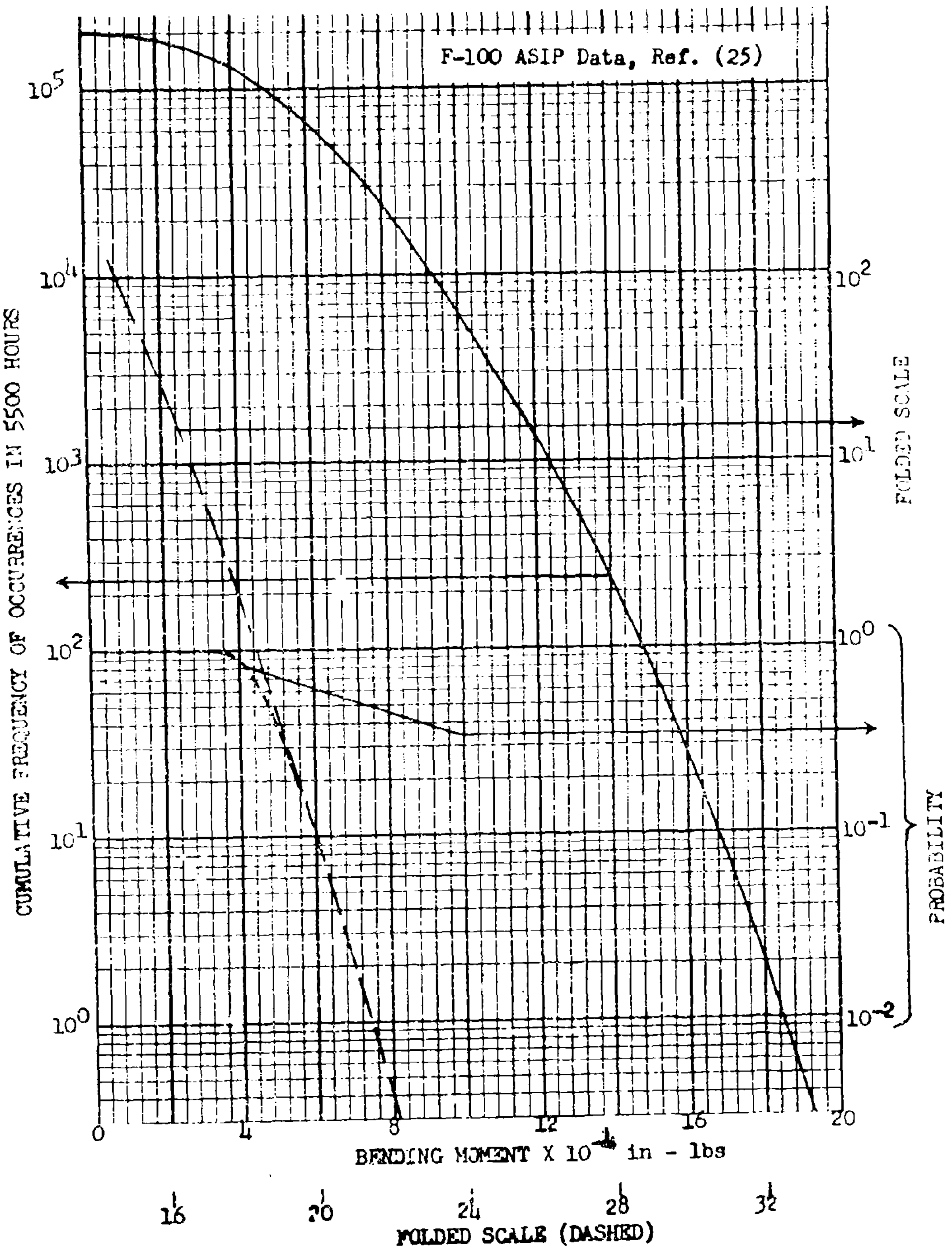


FIGURE 74. F-100 ASIP PHASE I VERTICAL TAIL ROOT BENDING MOMENT SPECTRUM

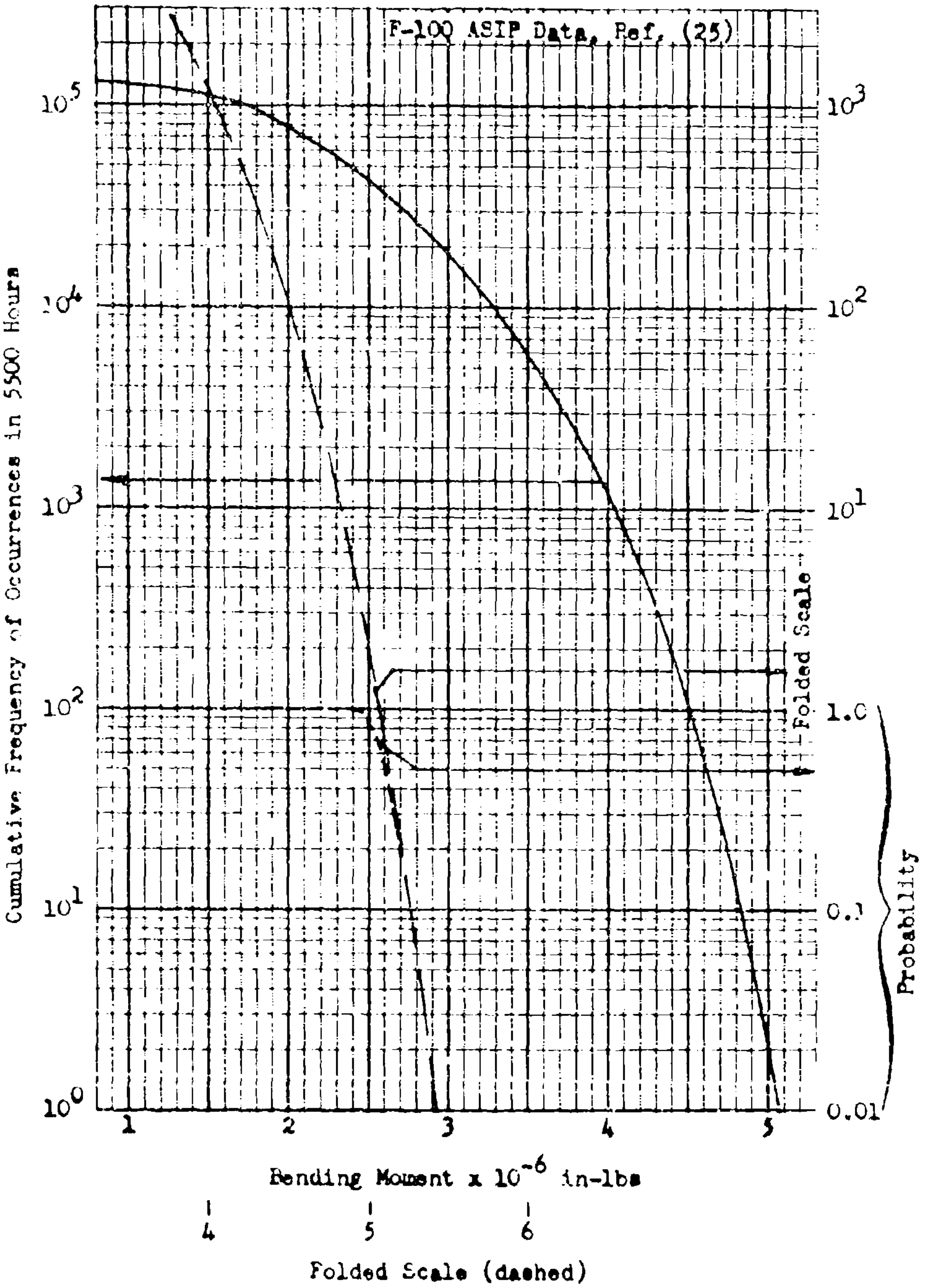


FIGURE 75. F-100 ASIP PHASE I WING ROOT BENDING MOMENT SPECTRUM (REV.)

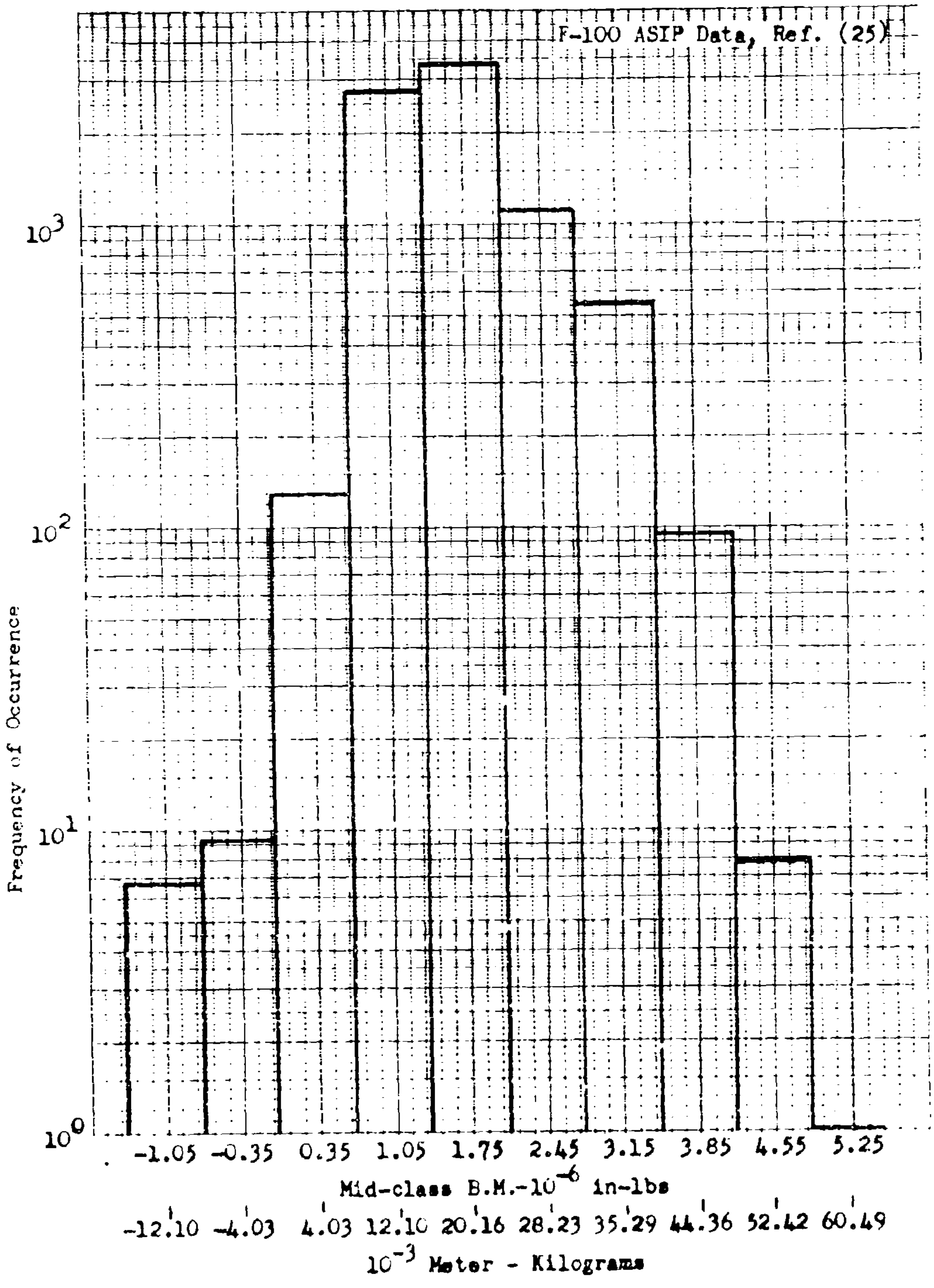


FIGURE 76. F-100 ASIP WING ROOT BENDING MOMENT HISTOGRAM

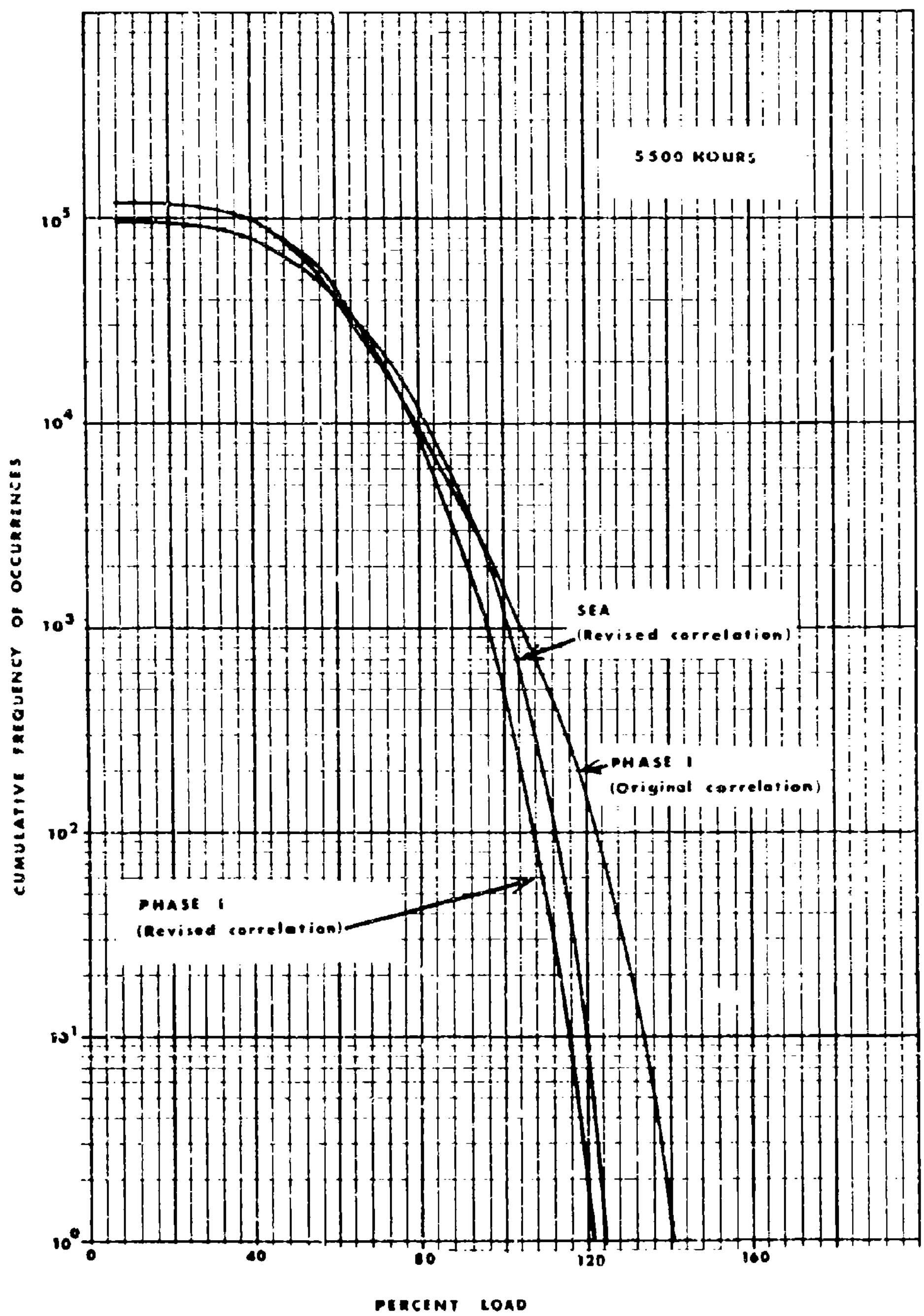


FIGURE 77. WING LOADING SPECTRA SUMMARY

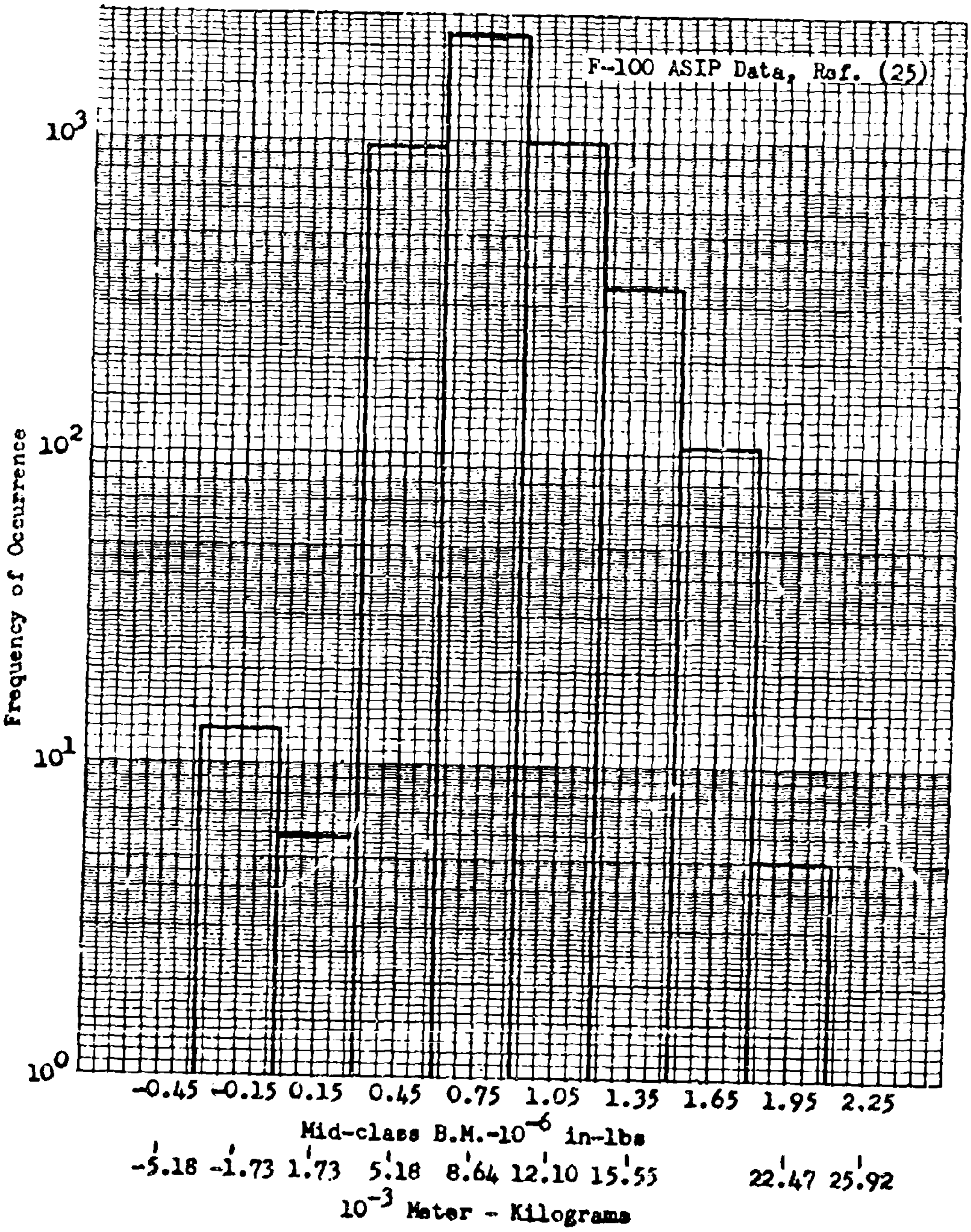


FIGURE 78. F-100 ASIP WING MIDSPAN BENDING MOMENT HISTOGRAM

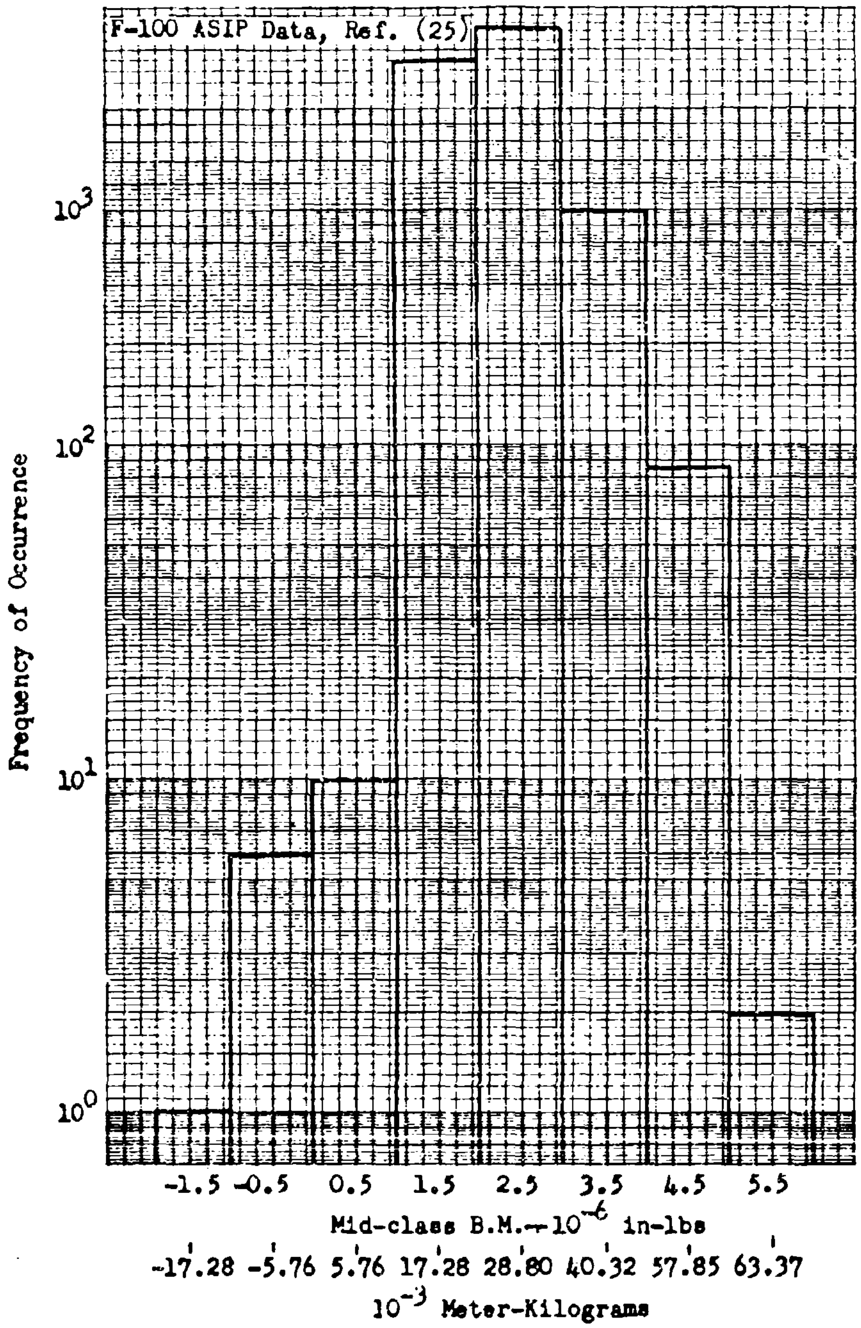


FIGURE 79. F-100 ASIP FUSELAGE STATION 310 BENDING MOMENT HISTOGRAM

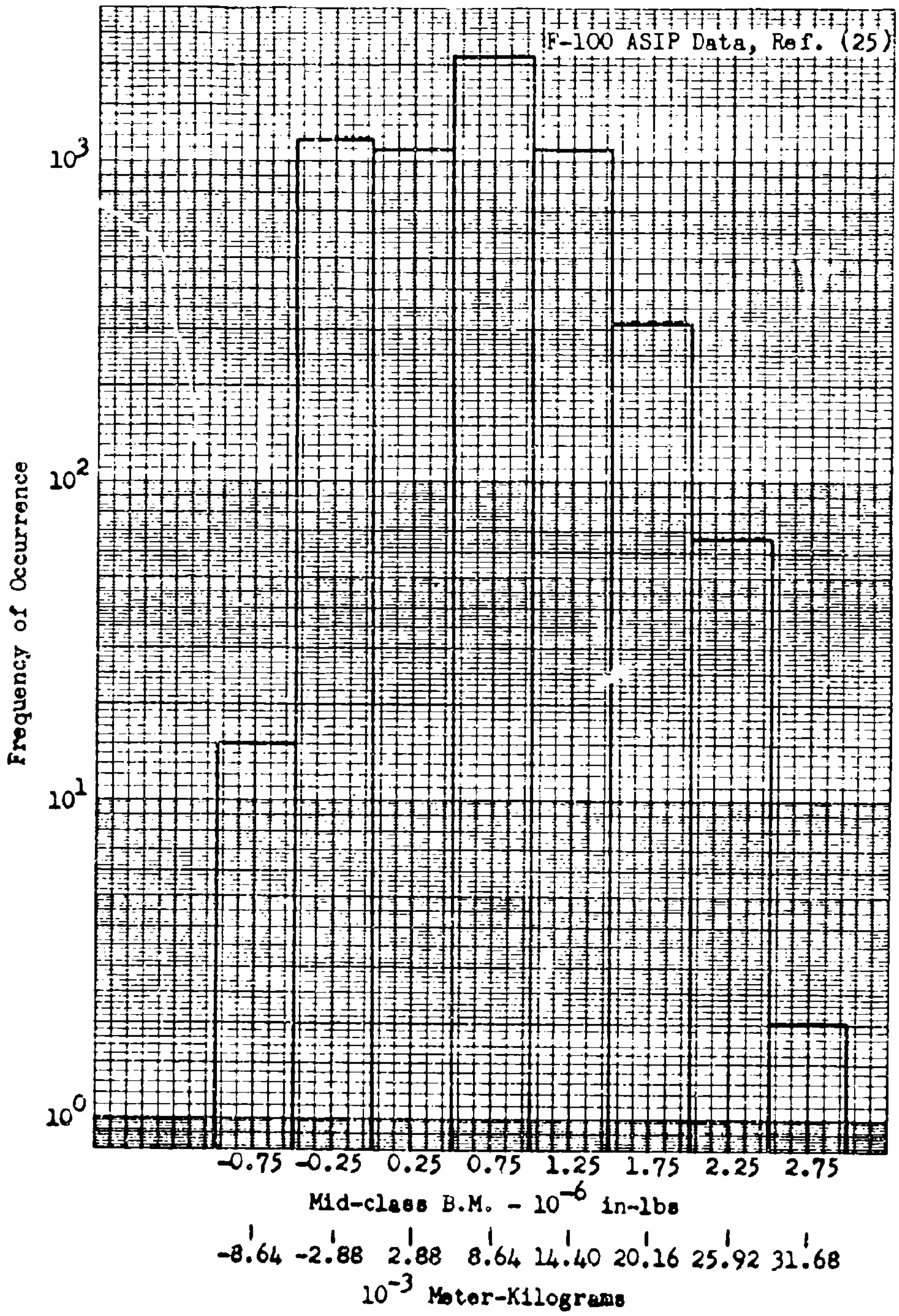


FIGURE 80. F-100 ASIP FUSELAGE STATION 369 BENDING MOMENT HISTOGRAM

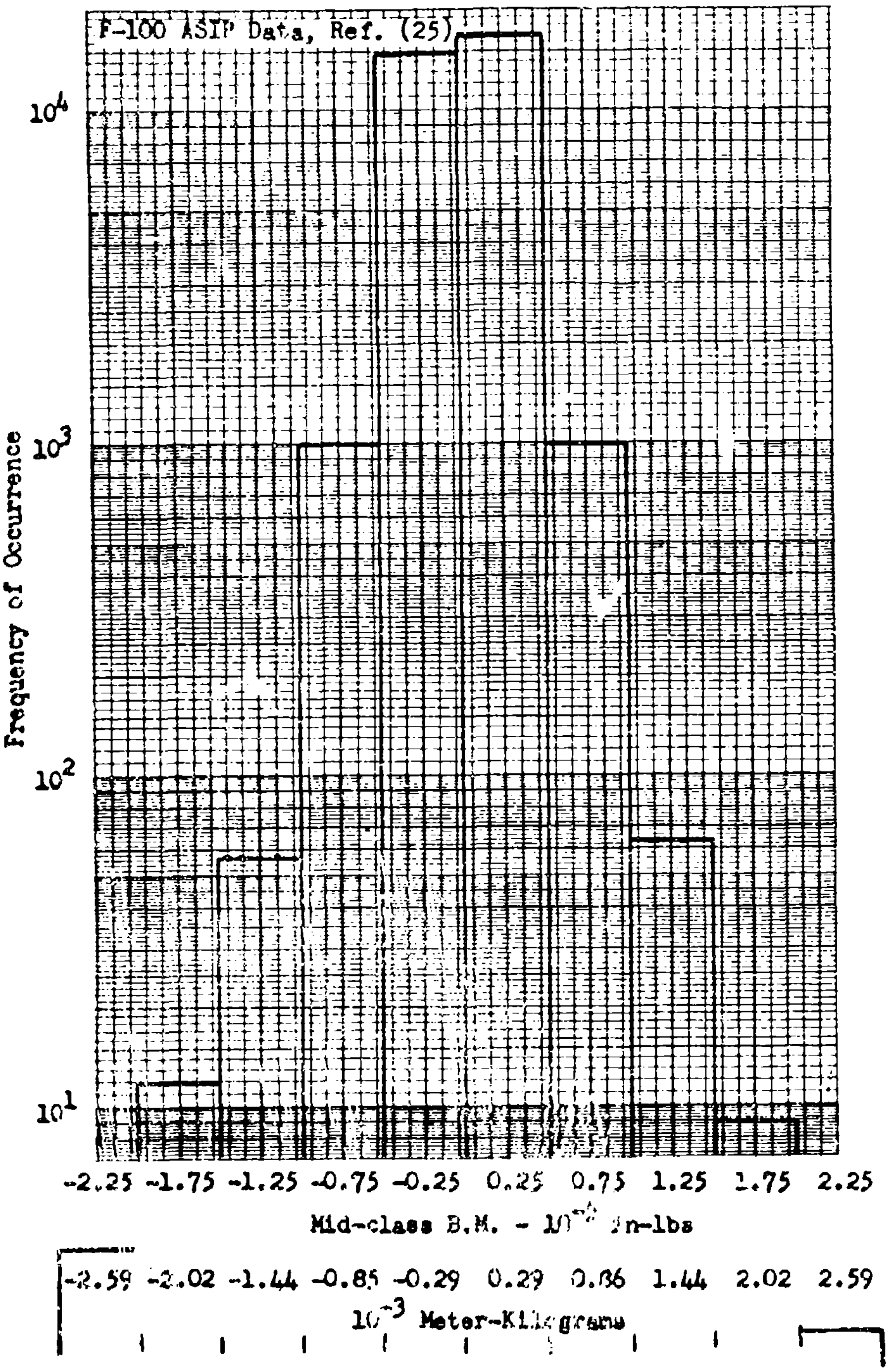


FIGURE 81. F-100 ASIP VERTICAL TAIL ROOT BENDING MOMENT HISTOGRAM

Mach number, whereas the critical wing and horizontal tail loads occur at high transonic Mach numbers at greater dynamic pressure. The usage loads therefore occur at higher airplane attack angles which are associated with inboard load centers of pressure and thus less bending moment than those at the critical design conditions. Limit values for the loads and load factors presented on Figure 67 are given on Table XX.

TABLE XX

F-100 ALLOWABLE LIMIT VALUES AT PERTINENT STATIONS - NORMAL
(Symmetric)

Normal Load Factor	n_z = +7.33 and -3.0 g's
	= +71.9 and -29.4 Meters/Sec.^{2}
Wing Root B.M. @ ASIP Strain Gage Station	M_x = 5.22$(10)^6$ in.-lbs.
	= 60.15$(10)^3$ Meter-Kilograms
Wing Midspan B.M. @ ASIP Strain Gage Station	M_x = 2.73$(10)^6$ in.-lbs.
	= 31.43$(10)^3$ Meter-Kilograms
Aft Fuselage Sta. 310 B.M.	M_y = 8.85$(10)^6$ in.-lbs.
	= 102$(10)^3$ Meter-Kilograms
Aft Fuselage Sta. 369 B.M.	M_y = 5.48$(10)^6$ in.-lbs.
	= 61.3$(10)^6$ Meter-Kilograms
Horizontal Tail Root B.M.	M_x = 0.64$(10)^6$ in.-lbs.
	= 7.375$(10)^3$ Meter-Kilograms

The lateral load factor usage spectra and loads versus percent of design limit load, Figure 68, are so small that they are insignificant. However, these spectra were applied in the structures laboratory where the tests were terminated after a scatter factor of four was attained. Limit values for the lateral factors are listed on Table XXI.

6.5 COMPUTER PROGRAM APPLICATIONS

a. Structural Reliability - Time-Independent (Static) Conditions

(1) General

The structural reliability computer program, whose principles are developed in Section 2.3, has been used to calculate a structural reliability

for the F-100. The details of the program, designated STRREL, are given in Volume III. The load spectra, presented in the previous section, are used to define the parameters used in the computations. The inputs to the computer are described in the next section and the probability of failure and structural reliability, as computed by the STRREL program, in the section following.

TABLE XXI

F-100 ALLOWABLE LIMIT VALUES AT PERTINENT STATIONS - LATERAL
(Asymmetric)

Lateral Load Factor	n_Y = 3.0 g's
	= 29.4 Meters/Sec.^{2}
Vertical Tail Root B.M.	M_x = 0.68$(10)^6$ in.-lbs.
	= 7.84$(10)^3$ Meter-Kilograms
Forward Fuselage Sta. 180 B.M.	M_z = 1.25$(10)^6$ in.-lbs.
	= 14.4$(10)^3$ Meter-Kilograms

(2) Input Data

The load input data for the STRREL program are generated from the spectra presented in Figures 67 and 68. Two points are used to define each load spectrum.

The points are chosen to provide the best possible fit of the available data in the region of most interest — at and above limit. Since data above limit are rarely available in great quantity, a point below limit may be used. For the F-100 data the two points used were limit and a point on the extrapolated curve above limit. The loading parameters for the resulting distributions were then determined by procedures described in Volume III. Since the computer program can be controlled to assume that the loads distribution is normal, log-normal or Weibull, each assumption was used. The resulting probability of exceeding load for each of the three types is shown on Figure 82. This figure shows the small differences between these three assumed distributions when they are all defined by the two points used in the computer program STRREL.

The strength input data for the F-100 are not easily determined. The structure is of conventional aluminum alloy construction which traditionally has small strength scatter. If the "A" and "B" allowables in MIL-HDBK-5[18] are assumed to represent 99% and 90% probabilities, respectively, a value of γ_s=.024 can be calculated for 7075-T6 aluminum alloy sheet. The variables added in manufacturing will increase this value considerably. No strength scatter data for the F-100 can be obtained from the hundreds of tests conducted because of the lack of duplication in the test program. However, a collection of test results from throughout the industry has shown that a value of γ_s ranging from about .02 to .08 may be expected for conventional construction.[2] Although the correct value for each location on the F-100 is not known, the reader may conservatively use the value γ_s = .08 to gain a "feel" for the significance of the computed results.

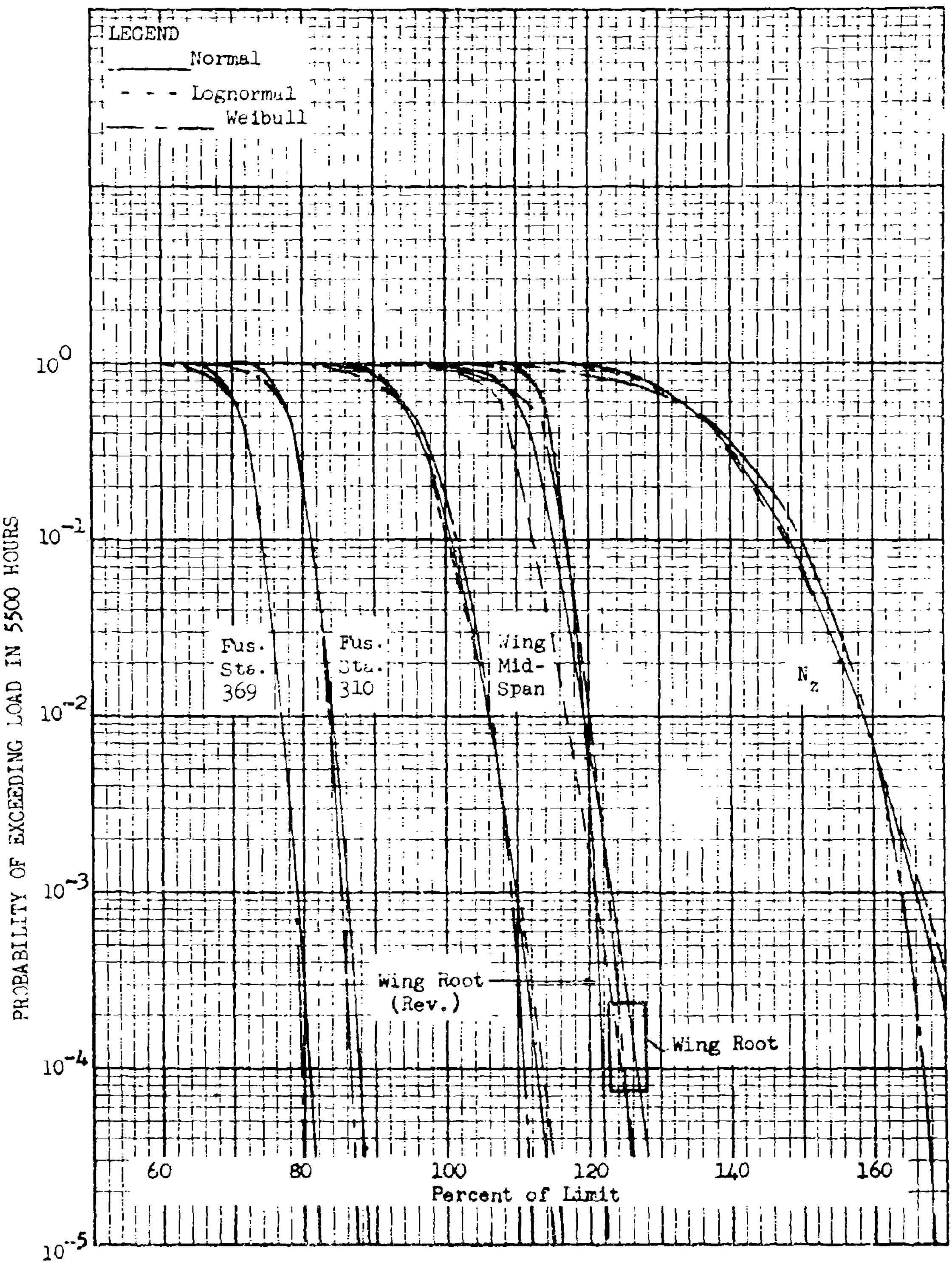


FIGURE 82. F-100 LOADING SPECTRA

(3) Computed Results

The structural reliabilities at the various wing and fuselage stations were computed for a range of strength scatter, γ_s. The results are plotted on Figures 83, 84 and 85, and summarized in Table XXII. The vertical tail loads were so low, as shown on Figure 68, that the numerical values were outside the capability of the STRREL program. Accordingly, vertical tail or fuselage side bending probabilities of failure are negligibly low and are not available.

TABLE XXII

F-100 COMPUTED STATIC STRUCTURAL RELIABILITIES

Assumed Distribution γ_s	Normal (Fig. 83)	Lognormal (Fig. 84)	Weibull (Fig. 85)
.05	.99993	.99993	.99987
.10	.9977	.9977	.996
.14	.991	.9912	.989

The minor difference between the results obtained using the three distributions illustrates the fact that the computed reliability of the structure is not sensitive to assumptions regarding the shape of the distribution functions. The reliability is much more sensitive to strength scatter than to variations in the loading and strength distributions, as shown by Figures 83, 84 and 85.

b. Structural Reliability - Time-Dependent (Fatigue) Conditions

(1) General

The fatigue reliability computer program, whose principles are developed in Section 2.4 and in Volume III, has been used to calculate a fatigue reliability for the F-100. The program is described in detail in Volume III. The load spectra presented in Section 6.4 are used to define parameters for computation. The formulation of the problem and the computer inputs are described in the next section and the results of the fatigue reliability calculations, as performed by the FATREL program, in the section following.

(2) Input Data

The load spectra used for the fatigue reliability calculations are based on the data given in Figure 82. These data were also used in setting up the fatigue test conditions in the F-100 ASIP program. This test program provided accurate stress data for the calculations. Figure 86 shows some typical stress versus load data from the wing root fillet area. The nonlinearity at high loads is due to plastic yielding of the wing plate material in the fillet area, which

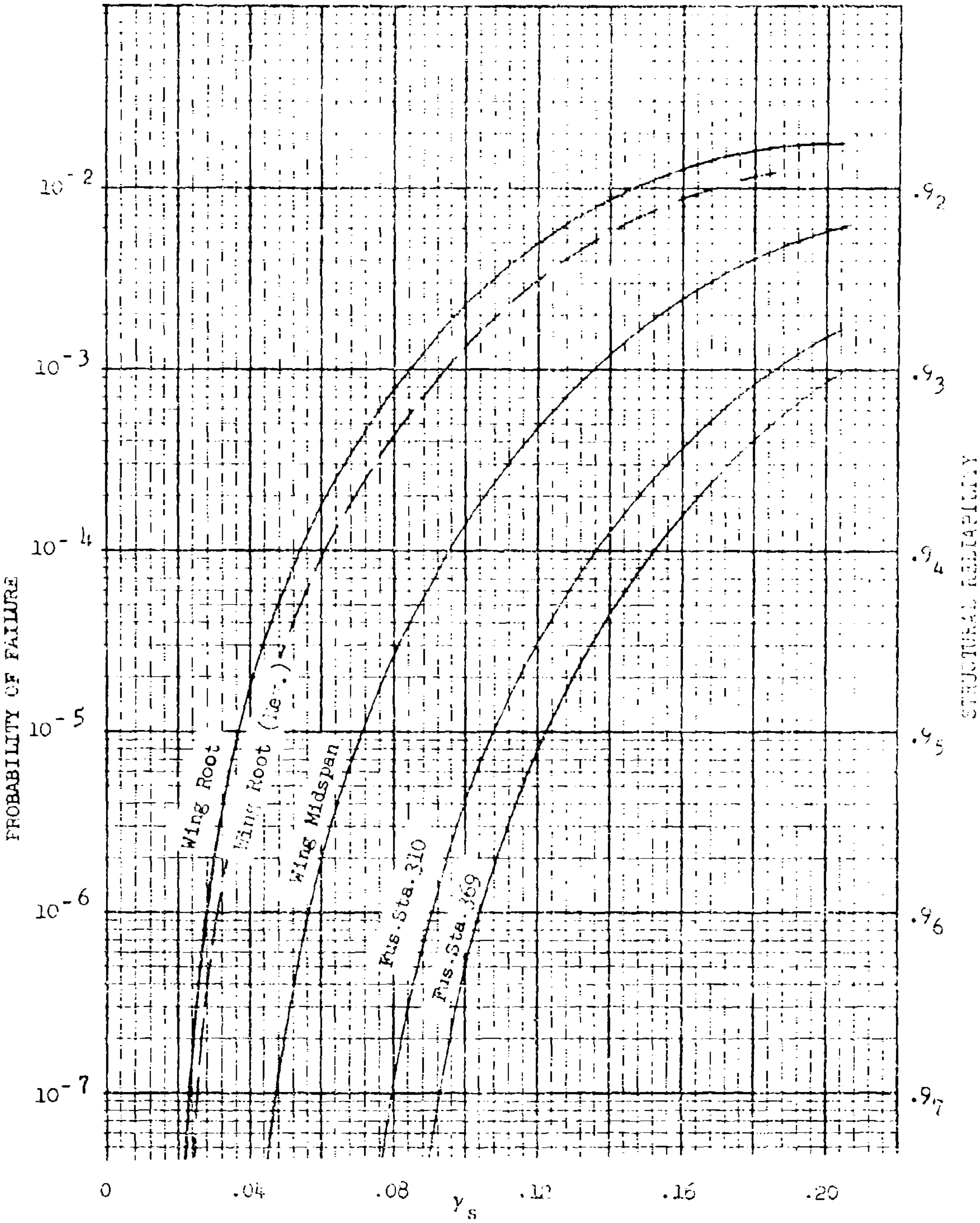


FIGURE 83. F-100 COMPUTED STATIC STRUCTURAL RELIABILITY - NORMAL STRENGTH AND LOAD DISTRIBUTION

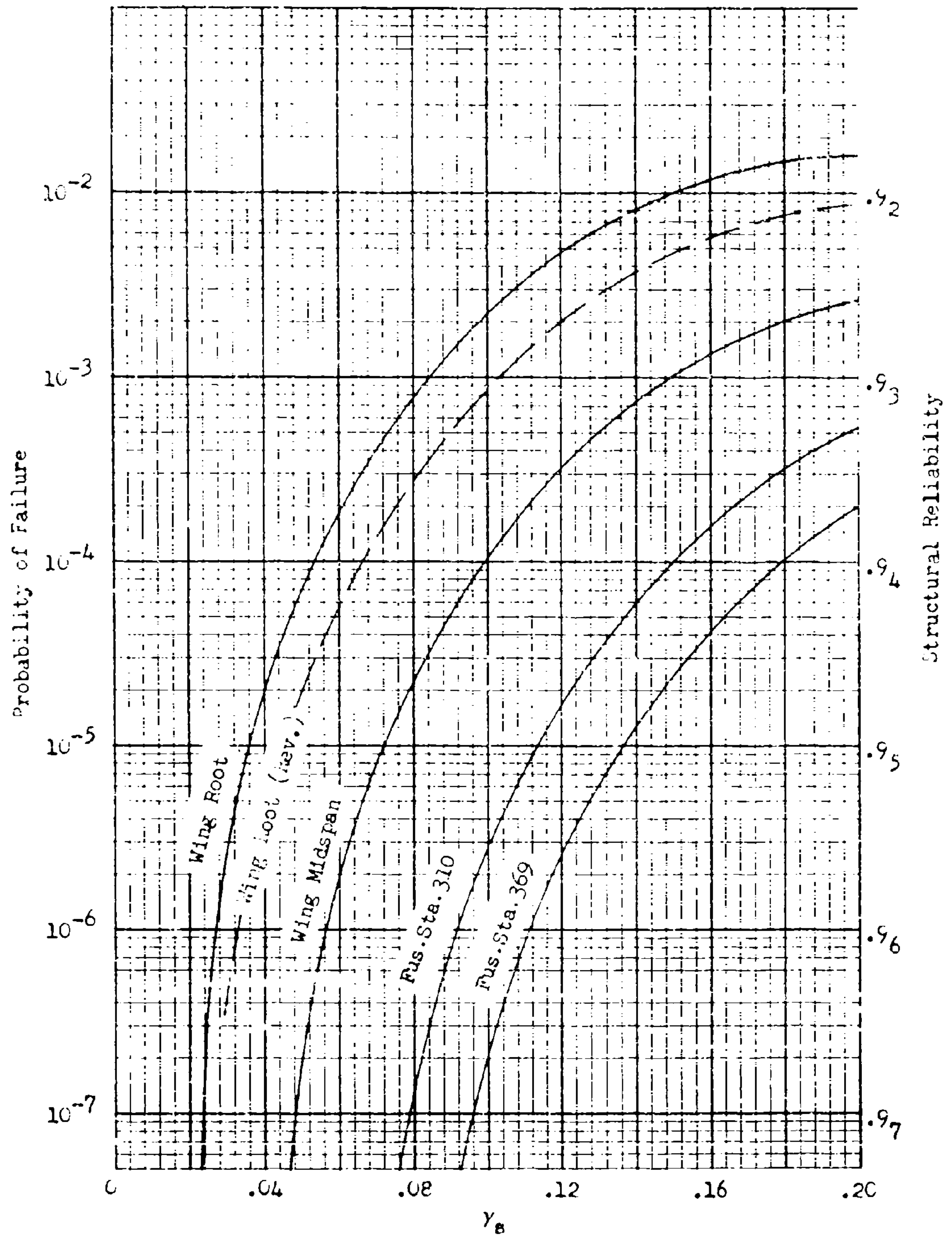


FIGURE 84. F-100 COMPUTED STATIC STRUCTURAL RELIABILITY - LOGNORMAL STRENGTH AND LOAD DISTRIBUTION

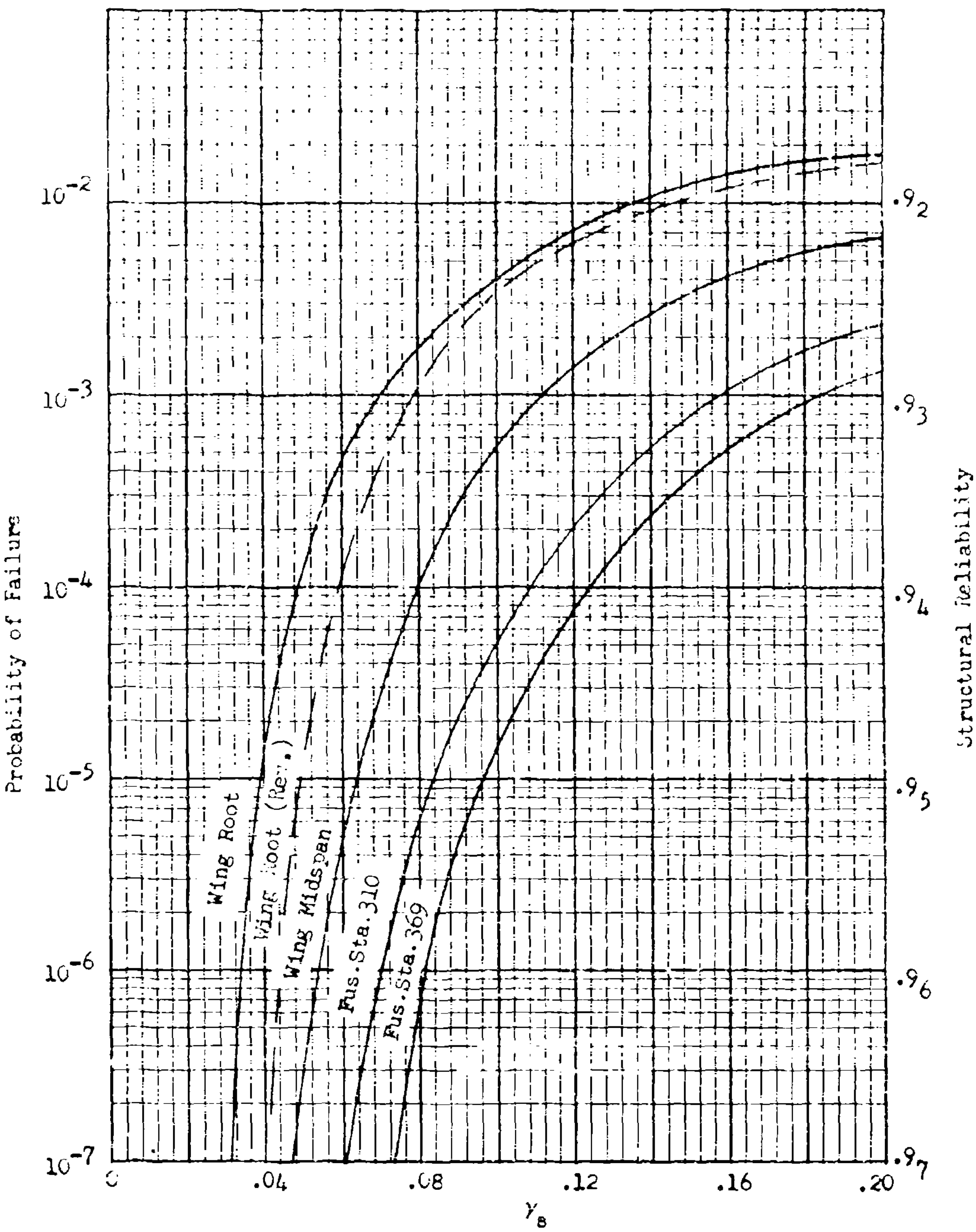
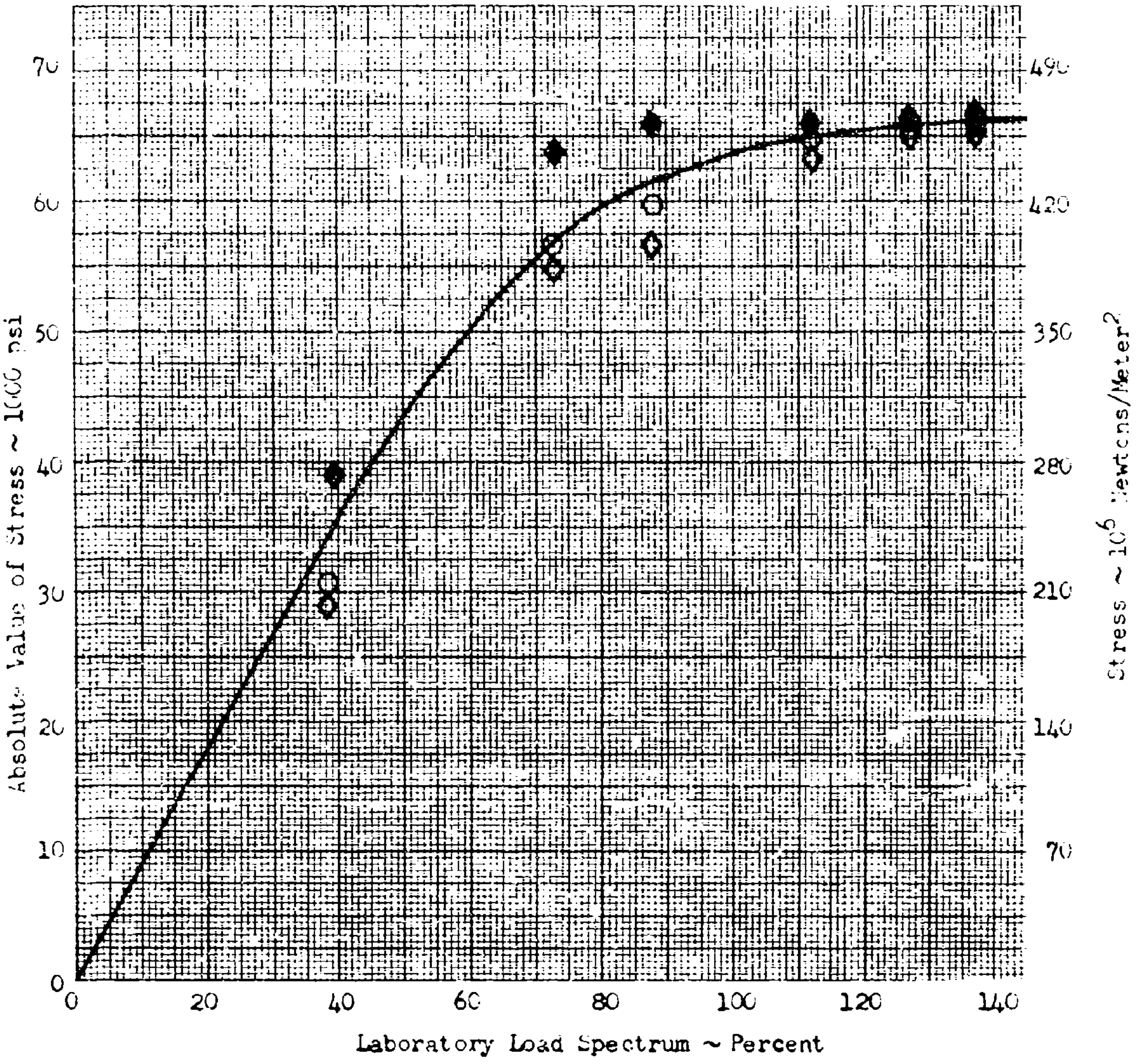


FIGURE 85. F-100 COMPUTED STATIC STRUCTURAL RELIABILITY - WEIBULL STRENGTH AND LOAD DISTRIBUTION



Legend

- ○ Left Upper Surface Compression
- ◇ Left Lower Surface Tension
- ◆ Right Lower Surface Modified 2 1/4 in. Radius

FIGURE 86 F-100 ASIP WING ROOT FILLET AREA STRESSES MEASURED IN LABORATORY TESTS

limits the maximum stresses at high loads. Although the stresses in Figure 86 are the highest recorded in the ASIP tests, failure occurred outboard of the root at a joint inboard of the main landing gear trunnion where strain gages were not applied. The loads applied to the wing during these fatigue tests are described by the bending moment spectra in Figure 70. Subsequent fatigue testing utilizes a revised bending moment spectrum delineated in Figure 75. The stress-bending moment curves for the wing root are given in Figures 87 and 88. Corresponding curves for other stations are given in Figures 89 to 92.

The differences in stress magnitudes shown on Figures 86 and 87, together with the fact of a test failure, indicates that a significant stress concentration existed at the point of fracture. In order to bracket the range of failure probabilities to be expected from the F-100, a distribution of stress concentration conditions was assumed for the computer program. The results from the various assumed values are shown in the next section.

Solution of the fatigue problem requires, in addition to the initial static strength data used in the static structural reliability calculations, an S-N curve describing the fatigue life characteristics of the basic material. The data used is shown in Figure 93. A folded scale is used to extrapolate the curve to 10^{12} cycles.

(3) Computed Results

The F-100 results from the fatigue computer program of Volume III of this report are shown for four airframe situations measured in the ASIP. The computed results are presented graphically as: (1) the cumulative probability of failure during fleet operation, Figures 94, 98, 102, 106, and 110; (2) the probability of passing laboratory tests, Figures 95, 99, 103, 107, and 111; (3) the probability of failing laboratory tests, Figures 96, 100, 104, 108, and 112; and (4) the probability of failure after tests - fleet operation, Figures 97, 101, 105, 109, and 113. These figures are grouped to show the results for the original wing root load spectrum (Figures 94-97), the wing root revised spectrum (Figures 98-101), the wing midspan (Figures 102-105), fuselage station 310 (Figures 106-109), and fuselage station 369 (Figures 110-113).

The computer program tabulations are not shown here since they are very similar to the second sample problem, the F-100 wing root, shown on pages 134 through 139 of Volume III. This wing root station load spectrum was revised midway in the ASIP program, Section 6.4d (bending moment spectra - correlation with load factors), to reflect the nonlinear trends with high angle of attack and/or normal load factor. The revised wing root has a somewhat higher S.R. as a result.

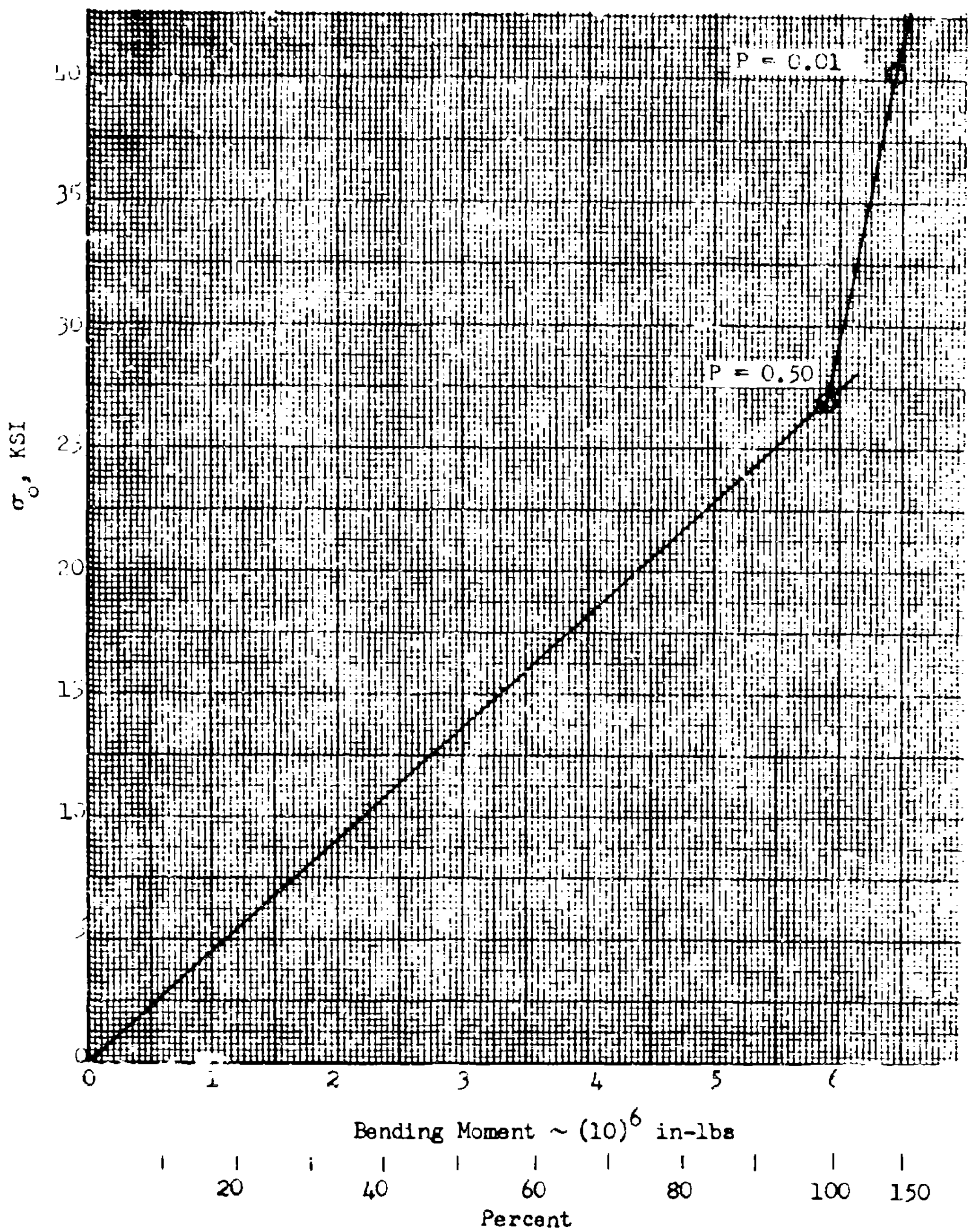


FIGURE 87. F-100 ASIP WING ROOT WORKING STRESSES FROM BENDING MOMENT SPECTRUM

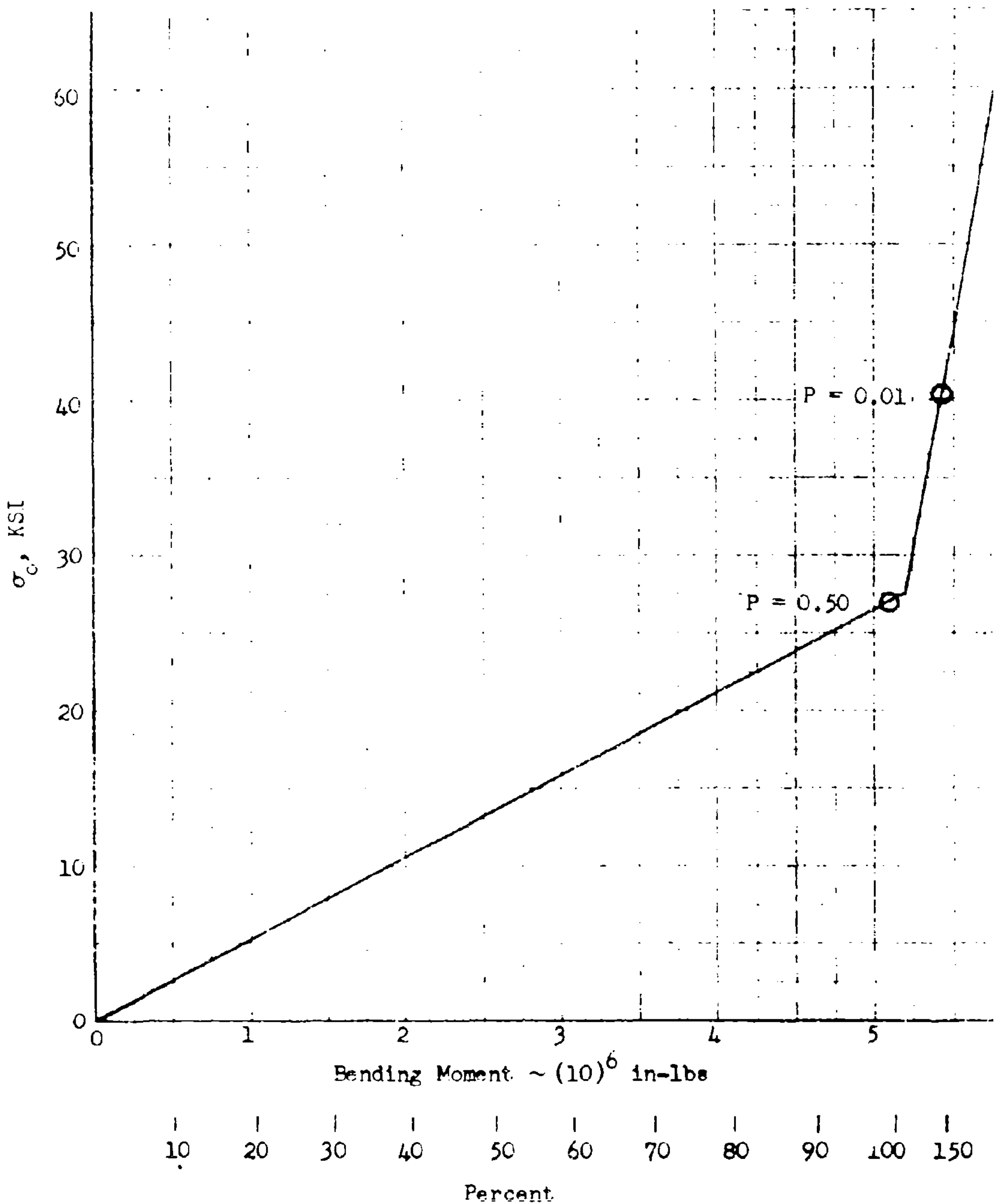


FIGURE 88. F-100 ASIP WING ROOT (REV.) WORKING STRESSES FROM BENDING MOMENT SPECTRUM

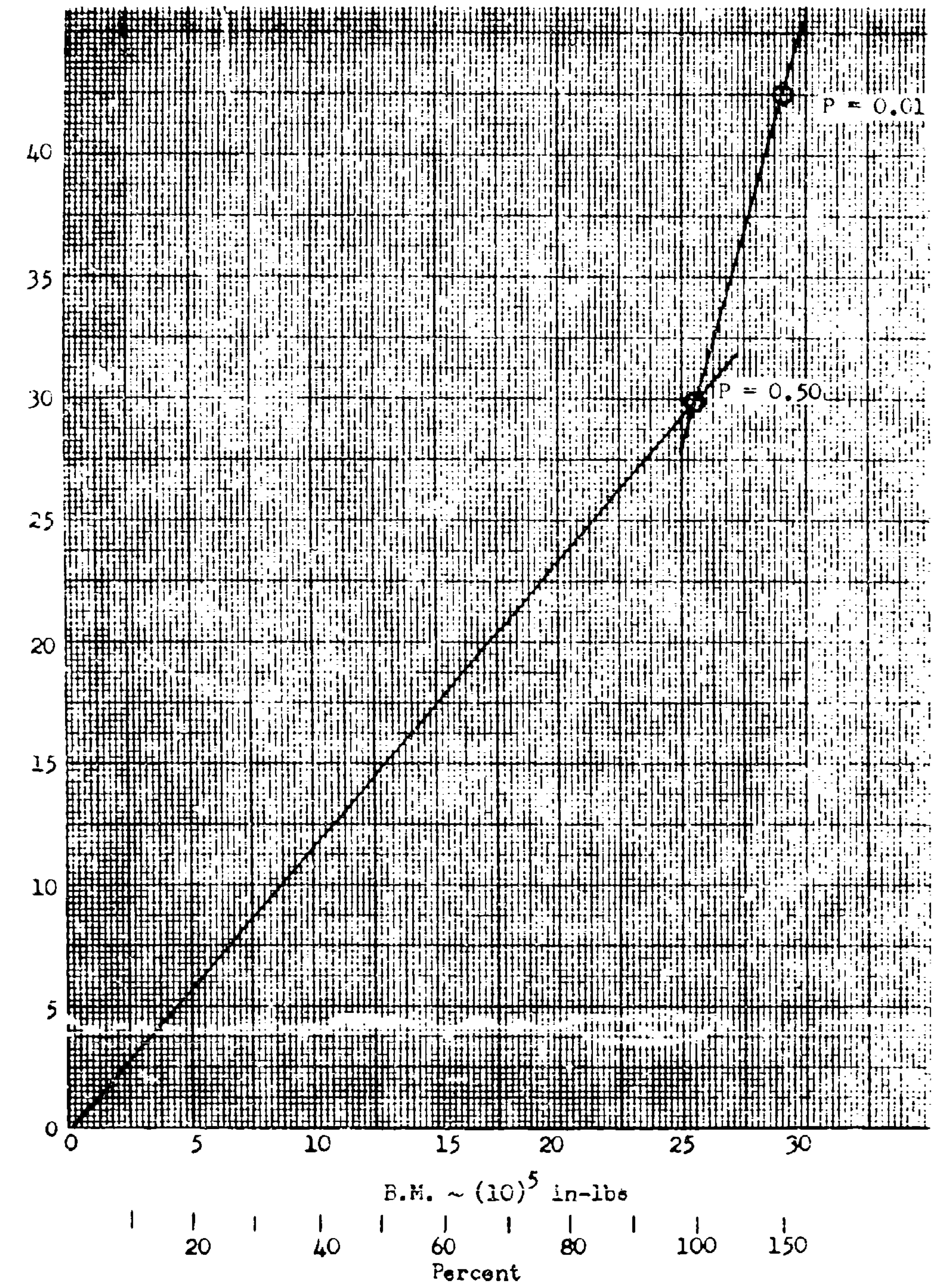


FIGURE 89. F-100 ASIP WING MIDSPAN WORKING STRESSES FROM BENDING MOMENT SPECTRUM

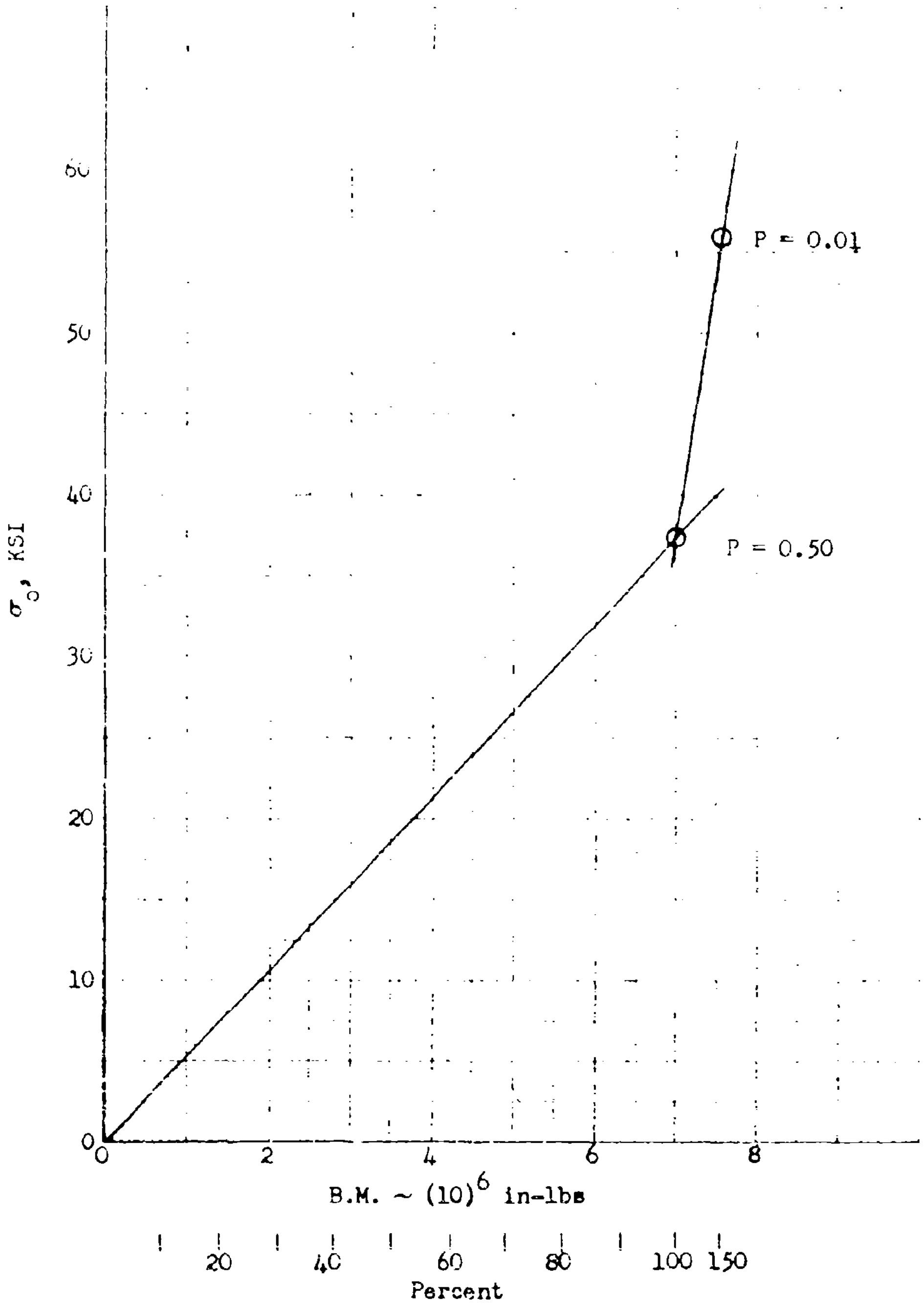


FIGURE 90. F-100 ASIP FUSELAGE STATION 310 WORKING STRESSES FROM BENDING MOMENT SPECTRUM

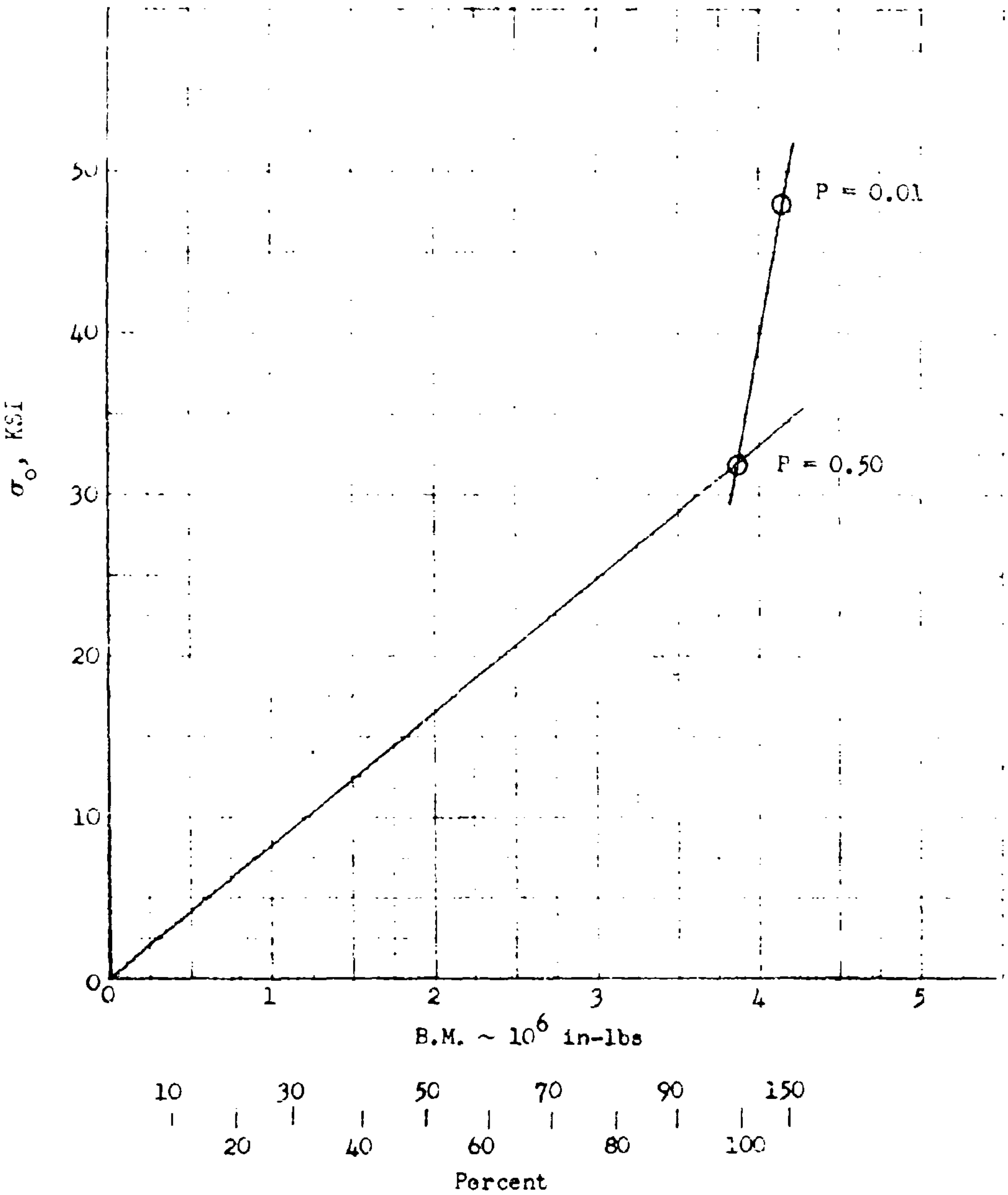


FIGURE 91. F-100 ASIP FUSELAGE STATION 369 WORKING STRESSES FROM BENDING MOMENT SPECTRUM

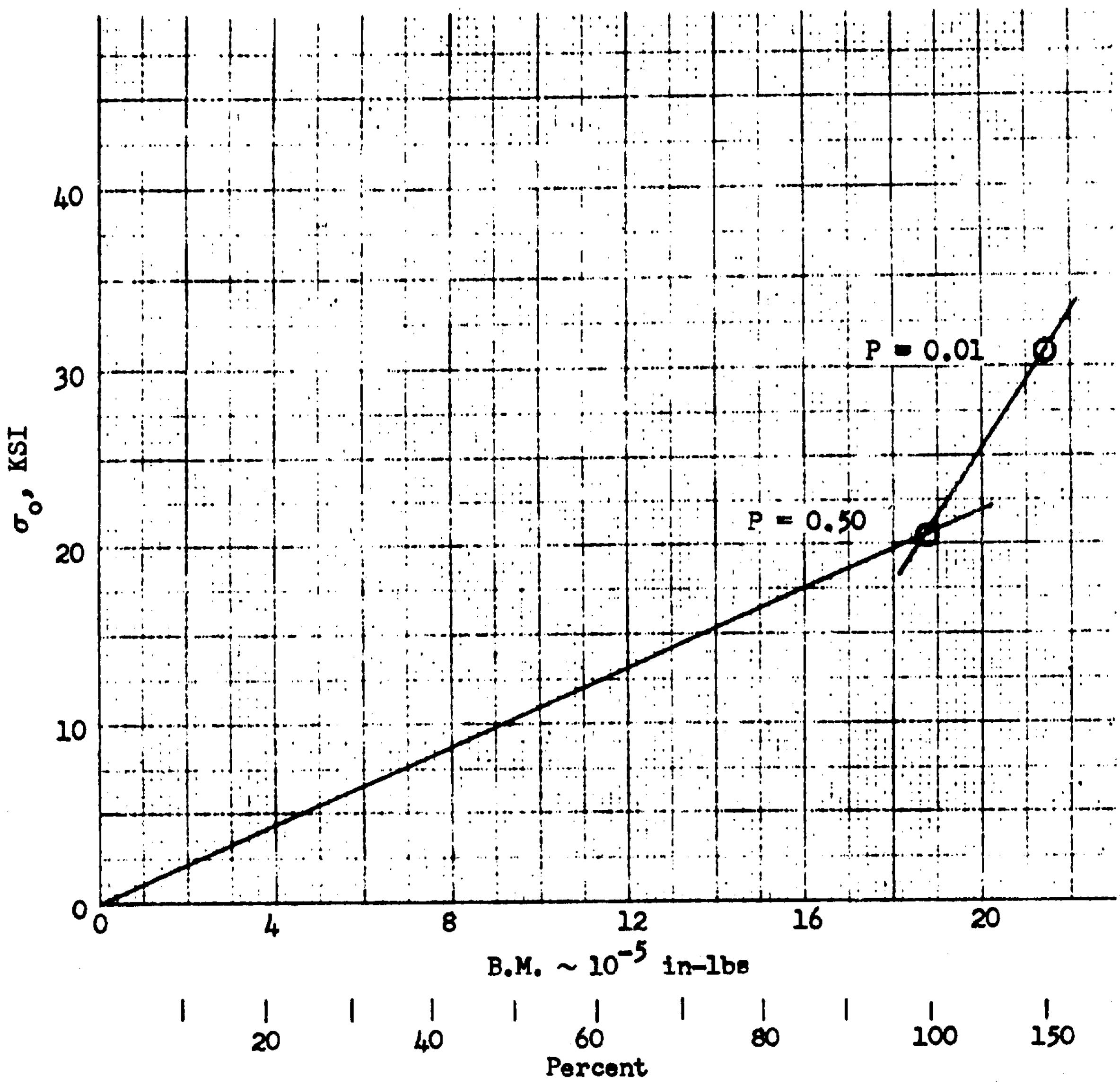


FIGURE 92. F-100 ASIP VERTICAL TAIL ROOT WORKING STRESSES FROM BENDING MOMENT SPECTRUM

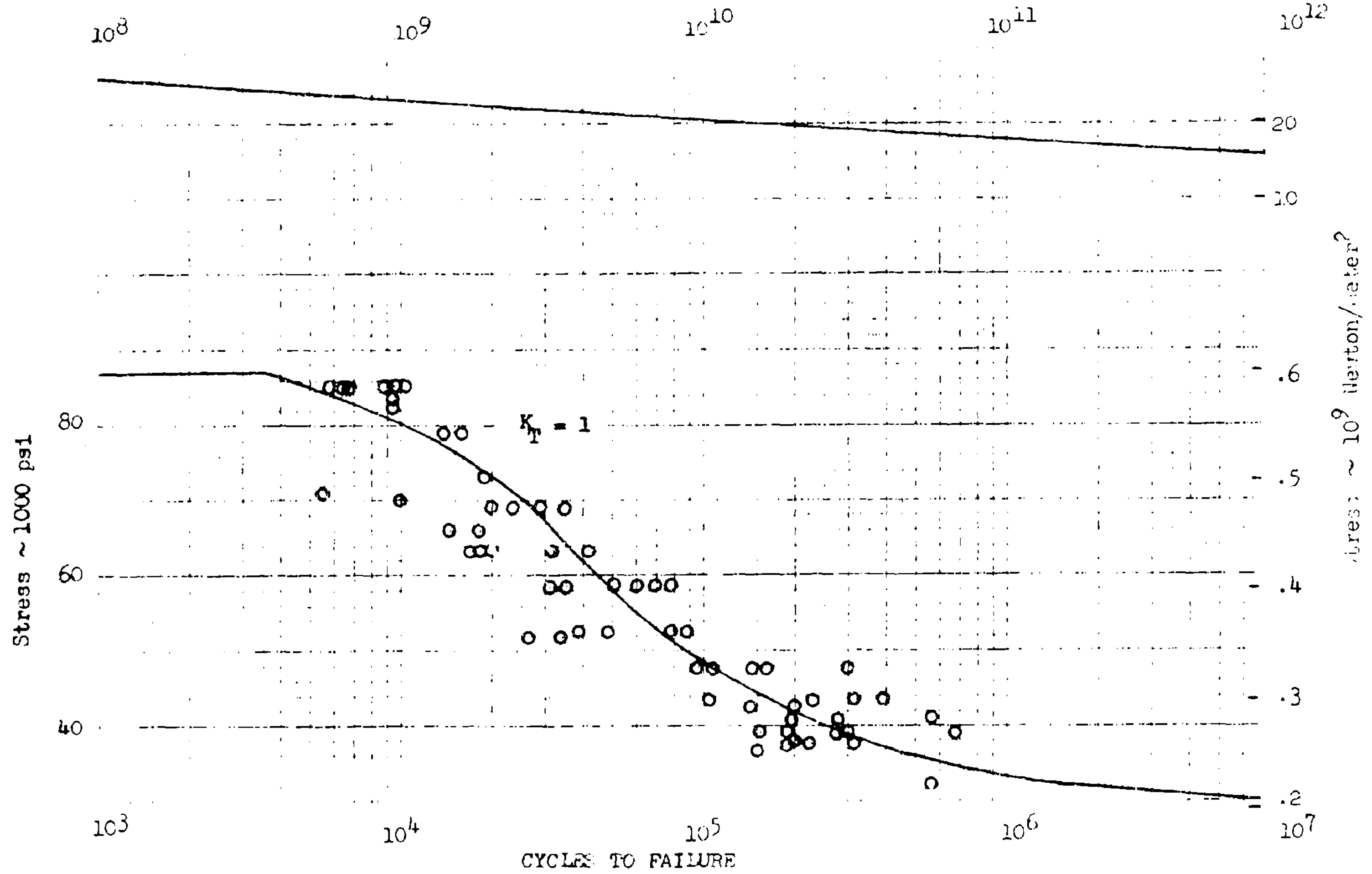


FIGURE 93. S-N CURVE 7075-T6 BARE SHEET, R = 0

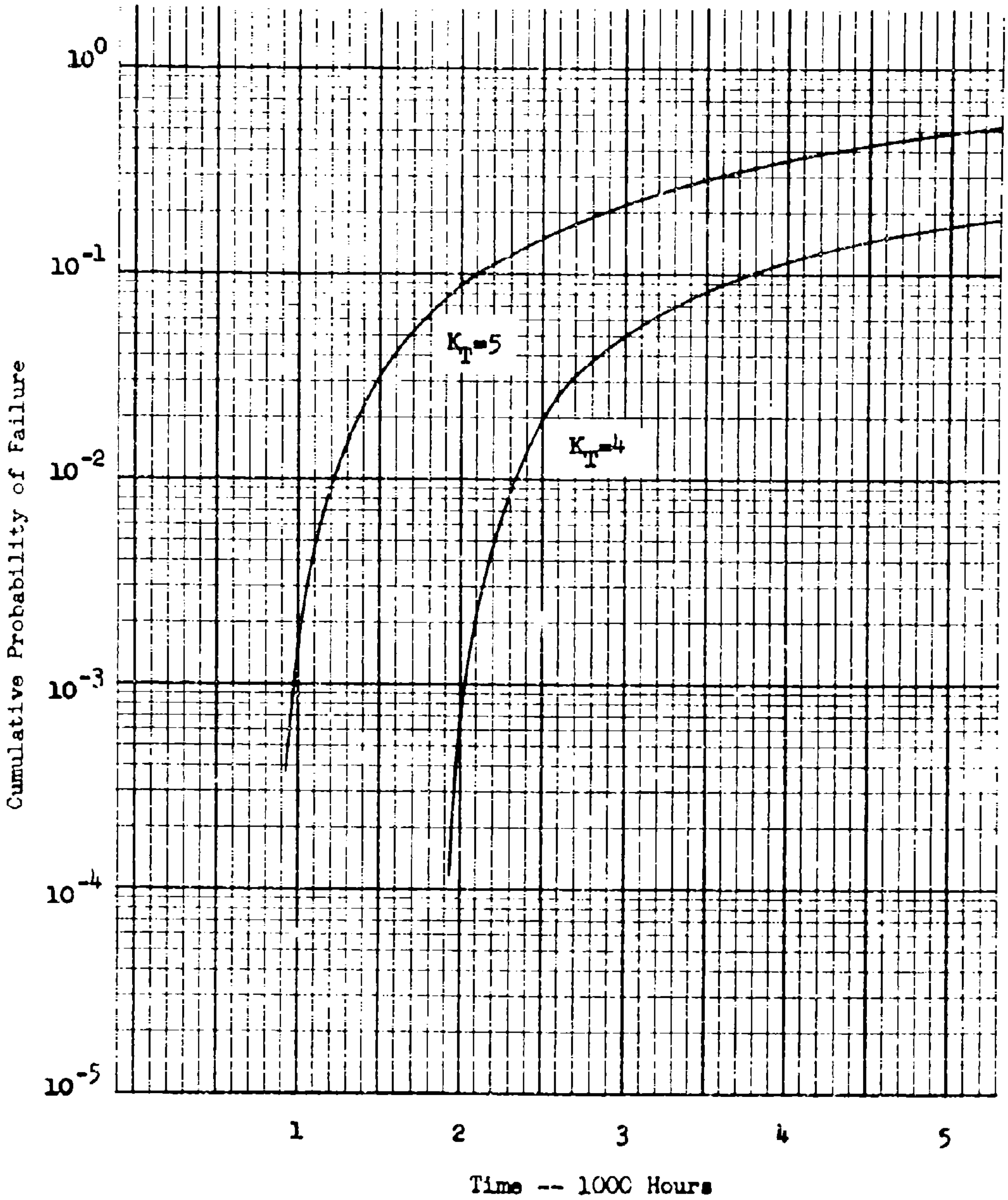
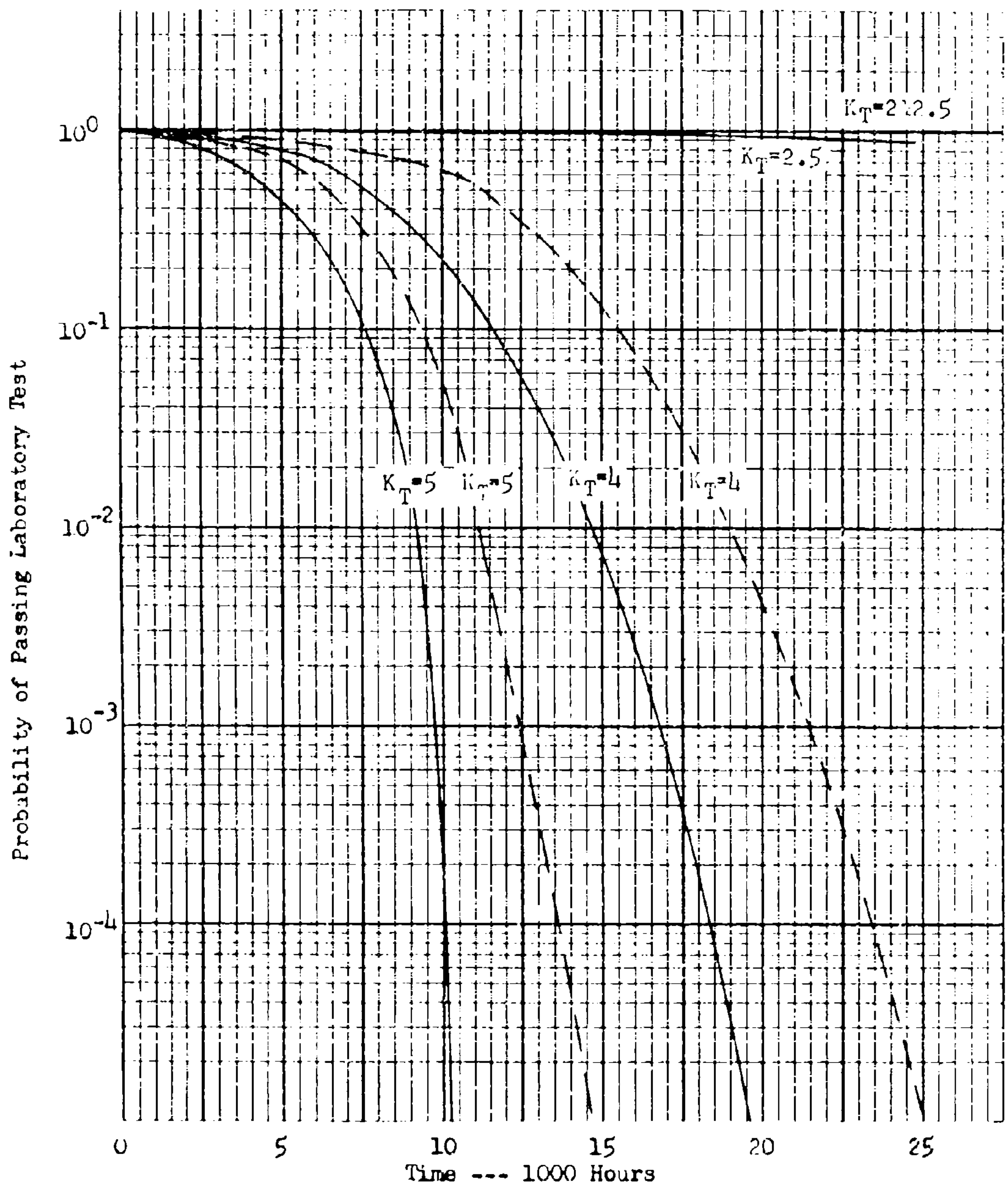


FIGURE 94. F-100 WING ROOT COMPUTED FATIGUE STRUCTURAL RELIABILITY - FLEET OPERATION S-N SCATTER = 4

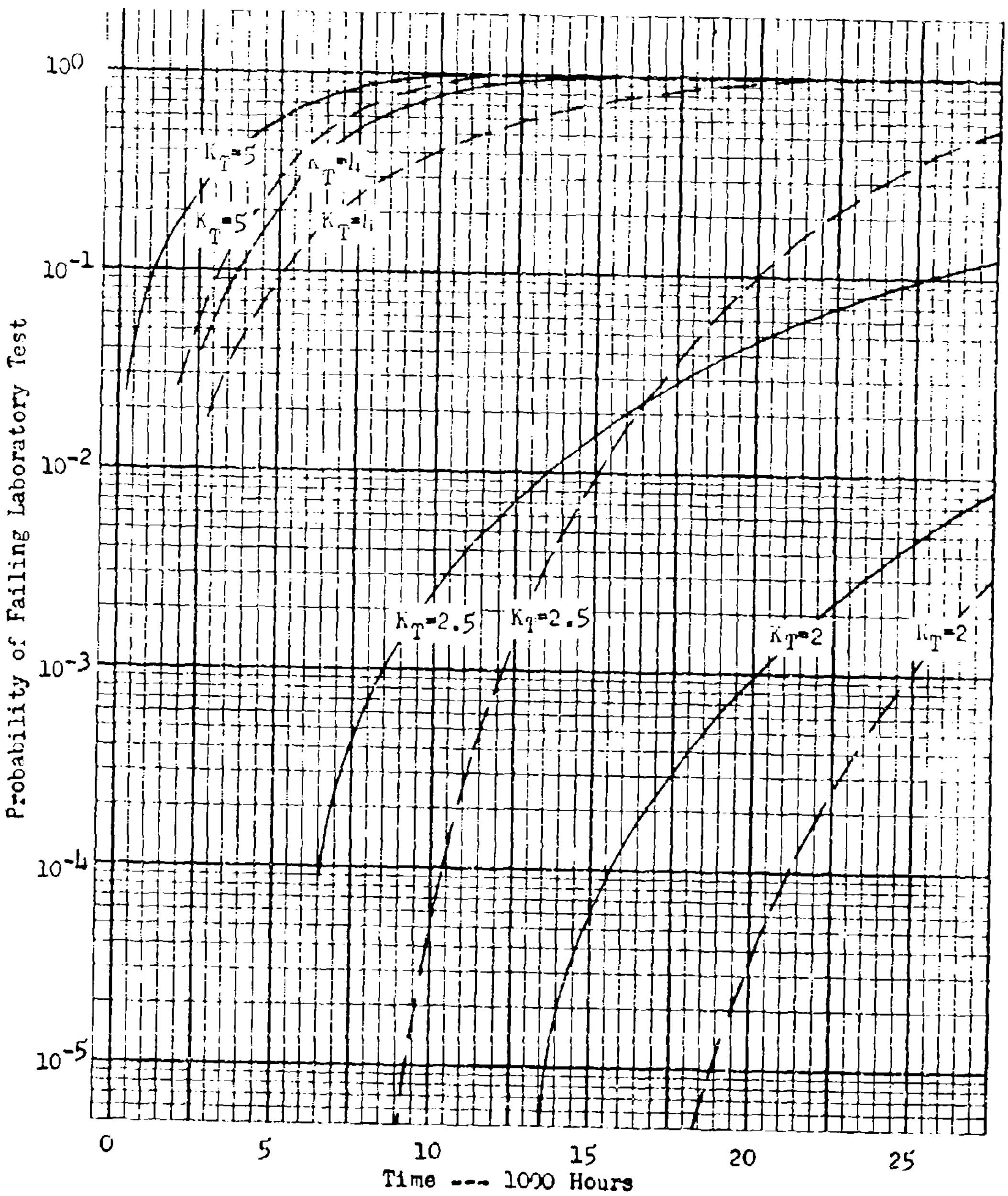


LEGEND

— — — Probability of Passing Fatigue Test

——— Probability of Passing Fatigue plus Static Test

FIGURE 95. F-100 WING ROOT COMPUTED FATIGUE STRUCTURAL RELIABILITY - PASSING PROBABILITY, TEST OPERATION S-N SCATTER = 4

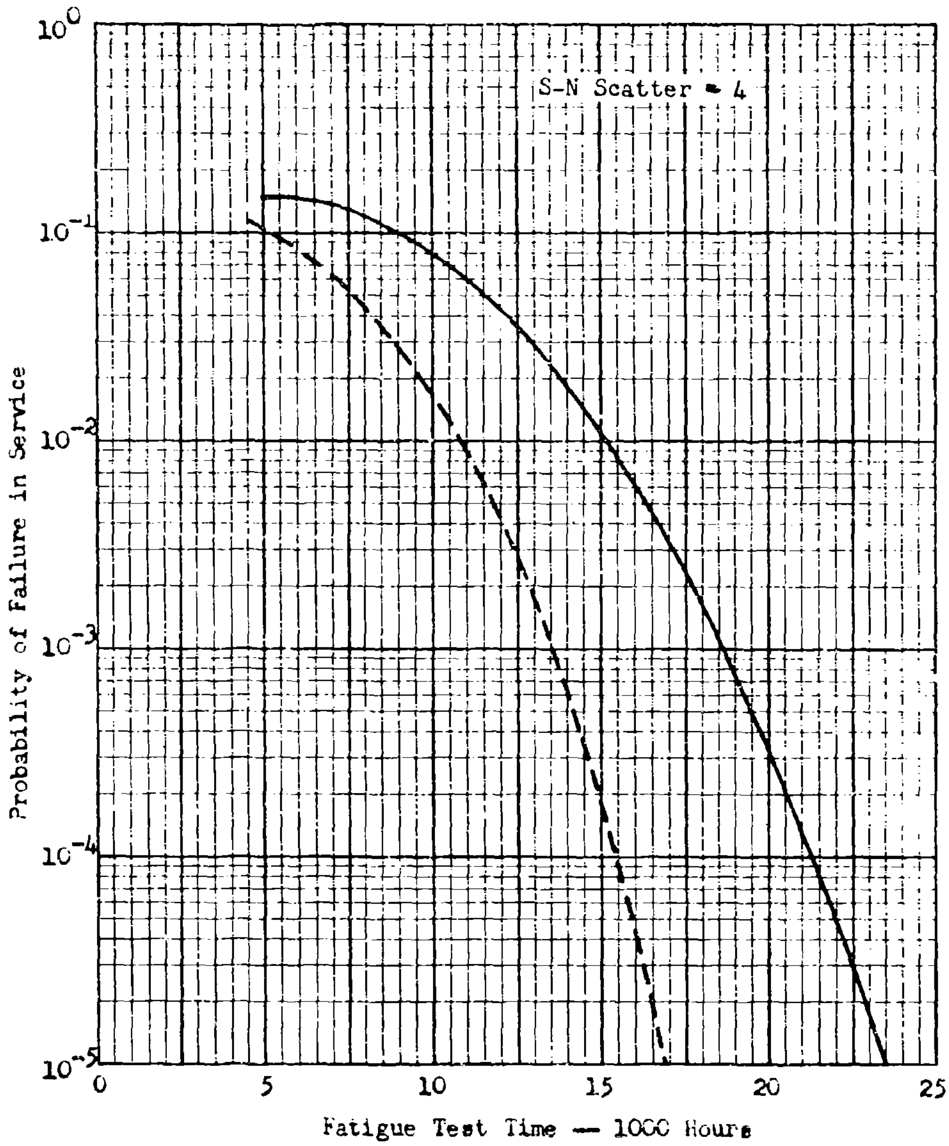


LEGEND

— — — Probability of Failing Fatigue Test

——— Probability of Failing Fatigue Test plus Static Test

FIGURE 96. F-100 WING ROOT COMPUTED FATIGUE STRUCTURAL RELIABILITY - FAILING PROBABILITY, TEST OPERATION S-N SCATTER = 4



LEGEND

—— After fatigue test

— — After fatigue test and static test

FIGURE 97. F-100 WING ROOT COMPUTED FATIGUE STRUCTURAL RELIABILITY-FAILURE PROBABILITY AT A NOMINAL LIFE OF 5500 HOURS AFTER TESTS - FLEET OPERATION

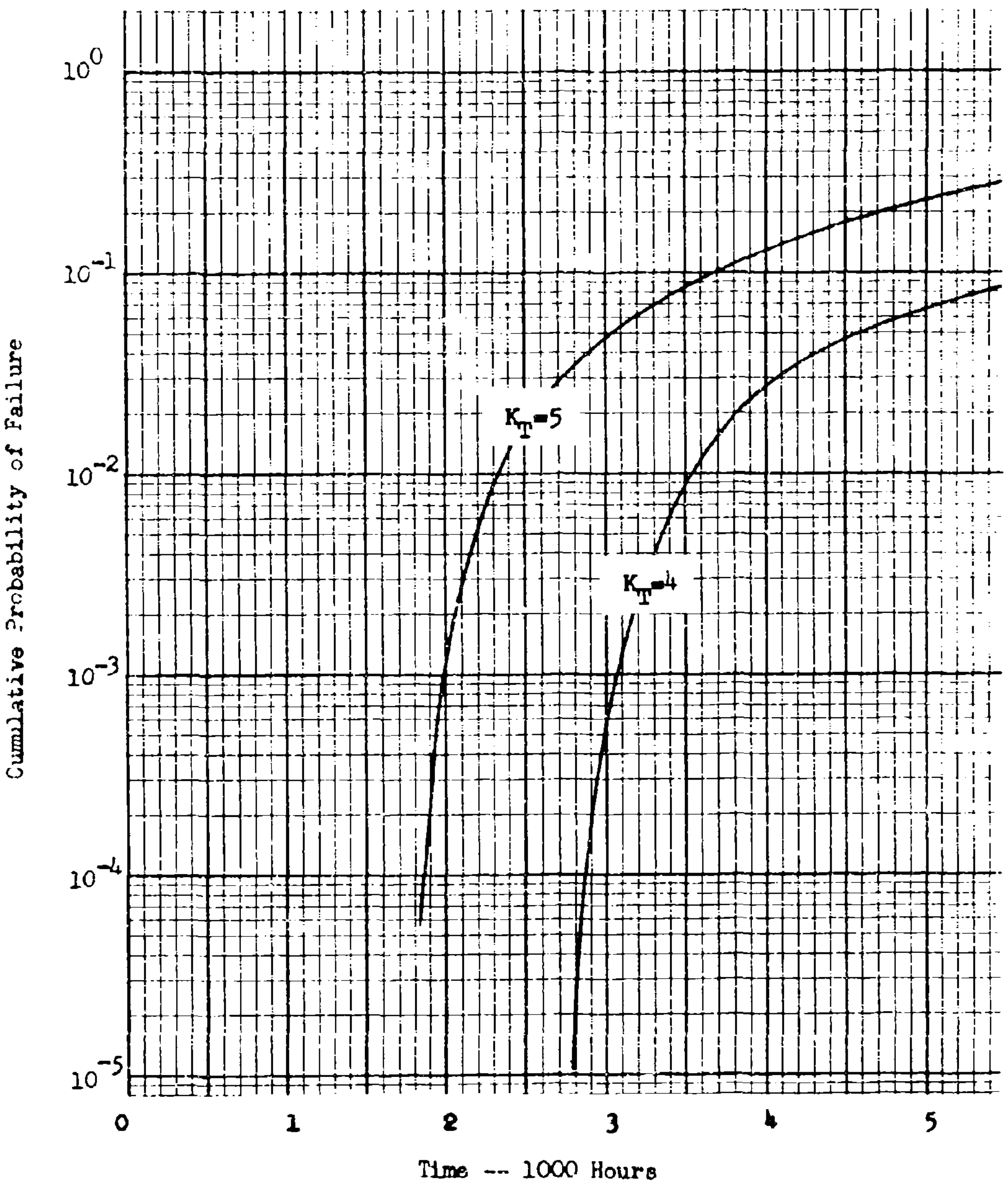
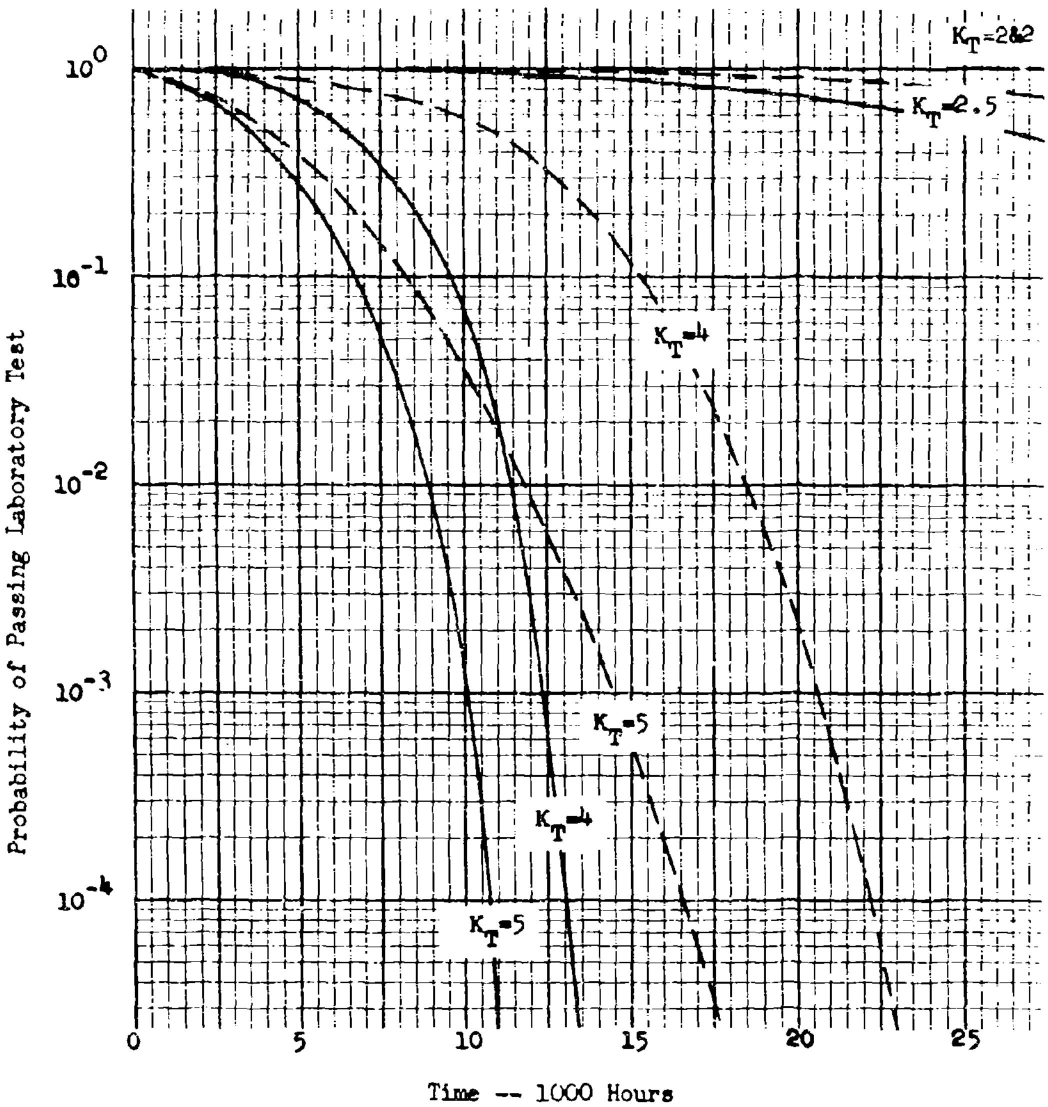


FIGURE 98. F-100 WING ROOT (REV.) COMPUTED FATIGUE STRUCTURAL RELIABILITY - FLEET OPERATION S-N SCATTER = 4

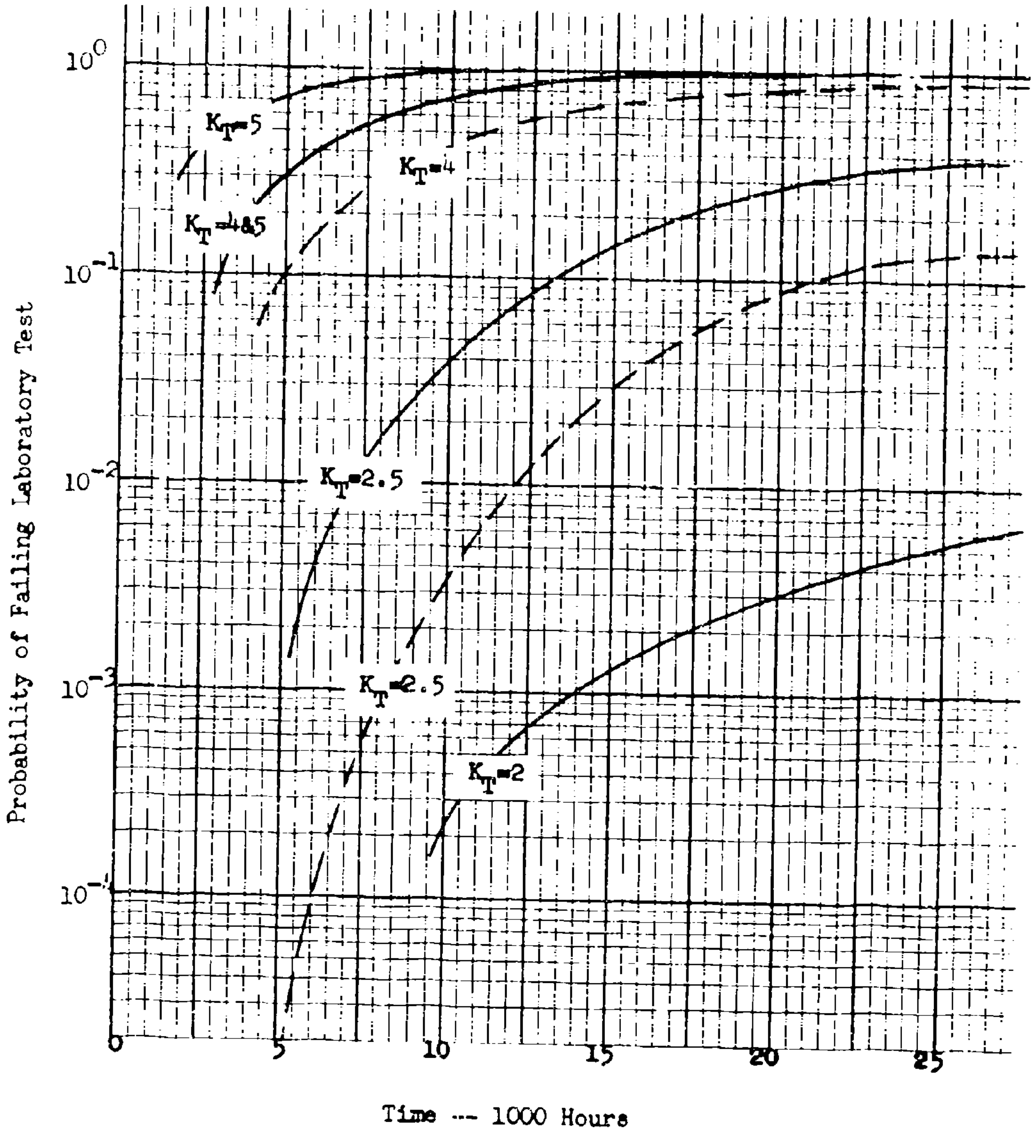


LEGEND

— — — Probability of Passing Fatigue Test

———— Probability of Passing Fatigue Test plus Static Test

FIGURE 99. F-100 WING ROOT (REV.) COMPUTED FATIGUE STRUCTURAL RELIABILITY - PASSING PROBABILITY, TEST OPERATION S-N SCATTER = 4

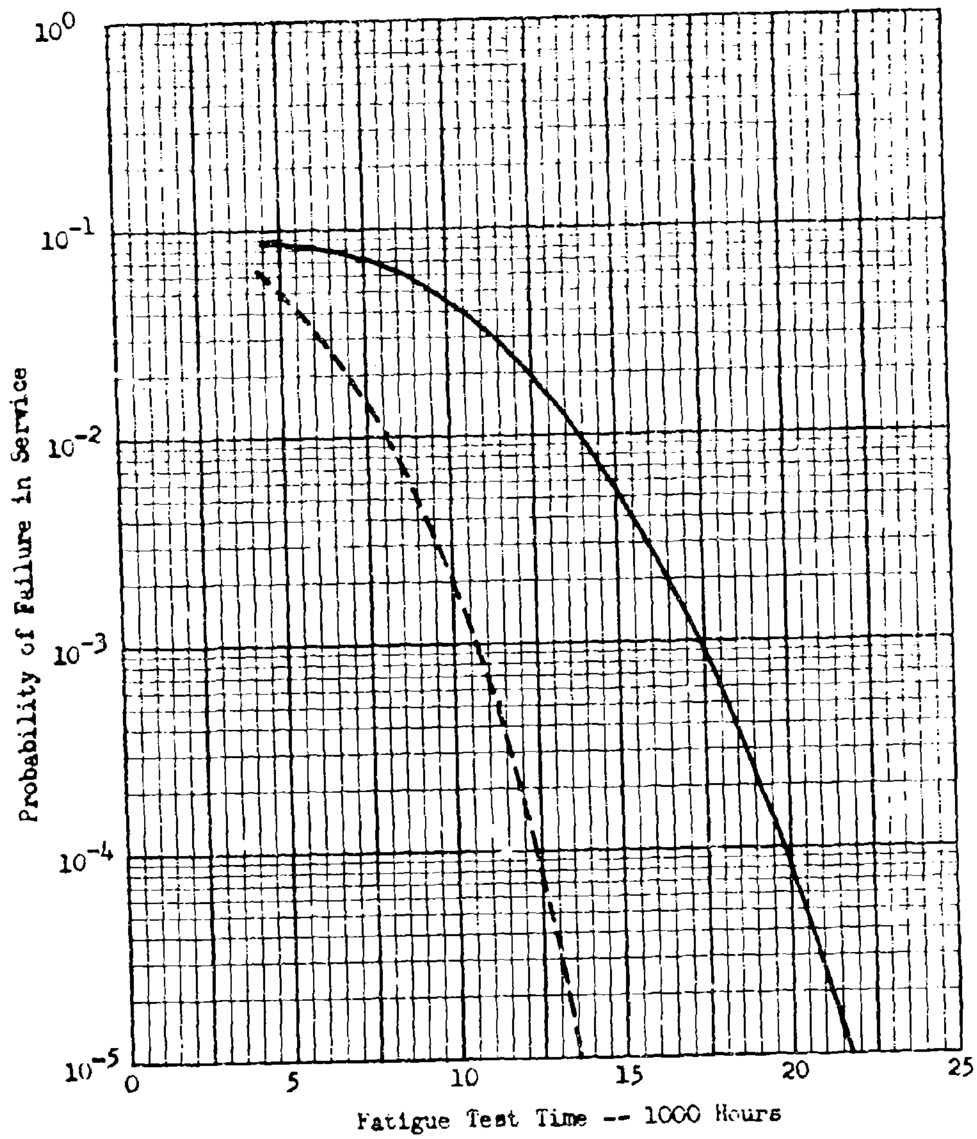


LEGEND

— — — Probability of Failing Fatigue Test

———— Probability of Failing Fatigue plus Static Test

FIGURE 100. F-100 WING ROOT (REV.) COMPUTED FATIGUE STRUCTURAL RELIABILITY - FAILING PROBABILITY, TEST OPERATION S-N SCATTER = 4



LEGEND

——— After Fatigue Test

— — After Fatigue and Static Test

S-N Scatter = 4

FIGURE 101. F-100 WING ROOT (REV.) COMPUTED FATIGUE STRUCTURAL RELIABILITY - FAILURE PROBABILITY AT A NOMINAL LIFE OF 5500 HOURS AFTER TESTS -- FLEET OPERATION

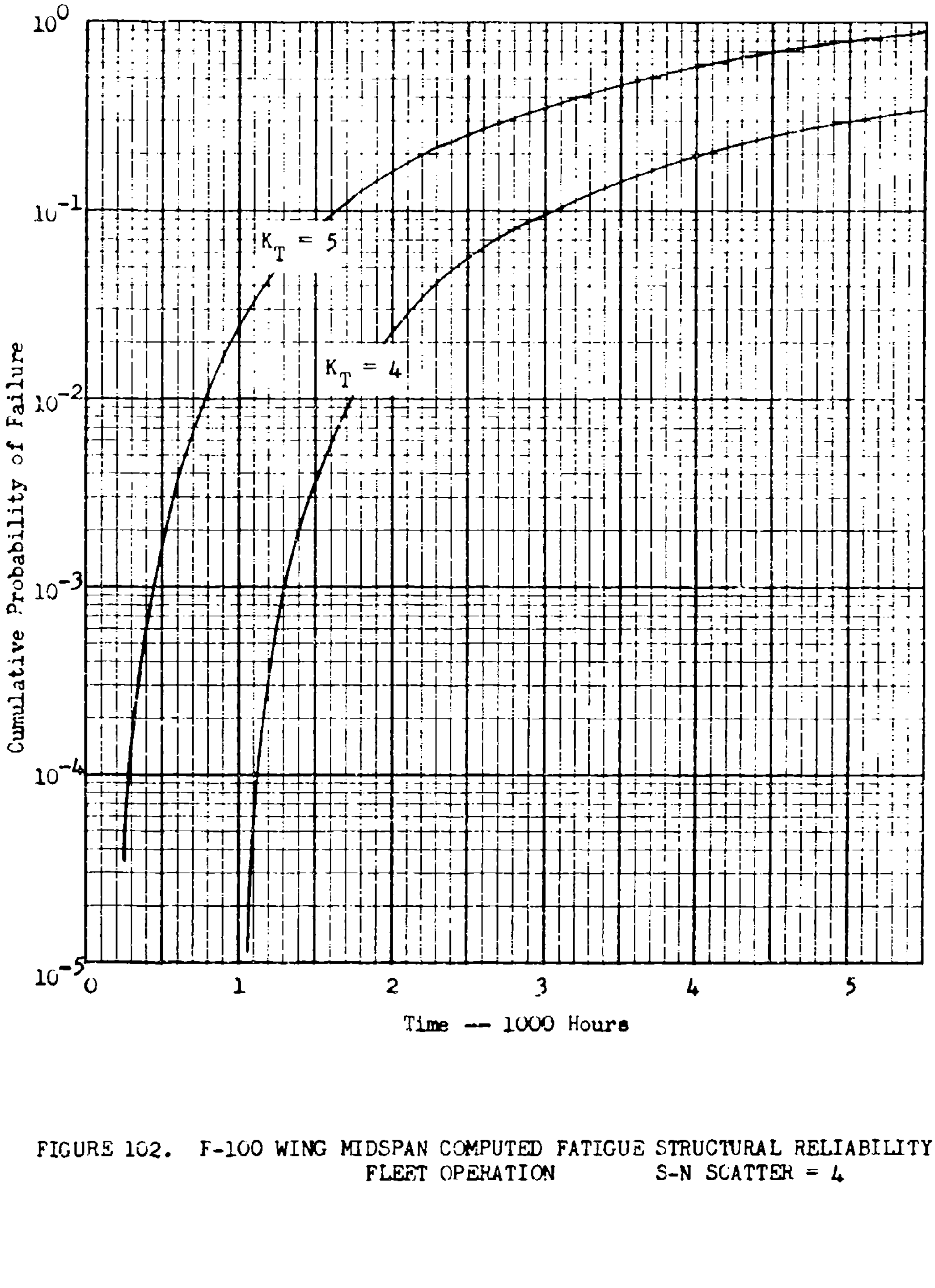
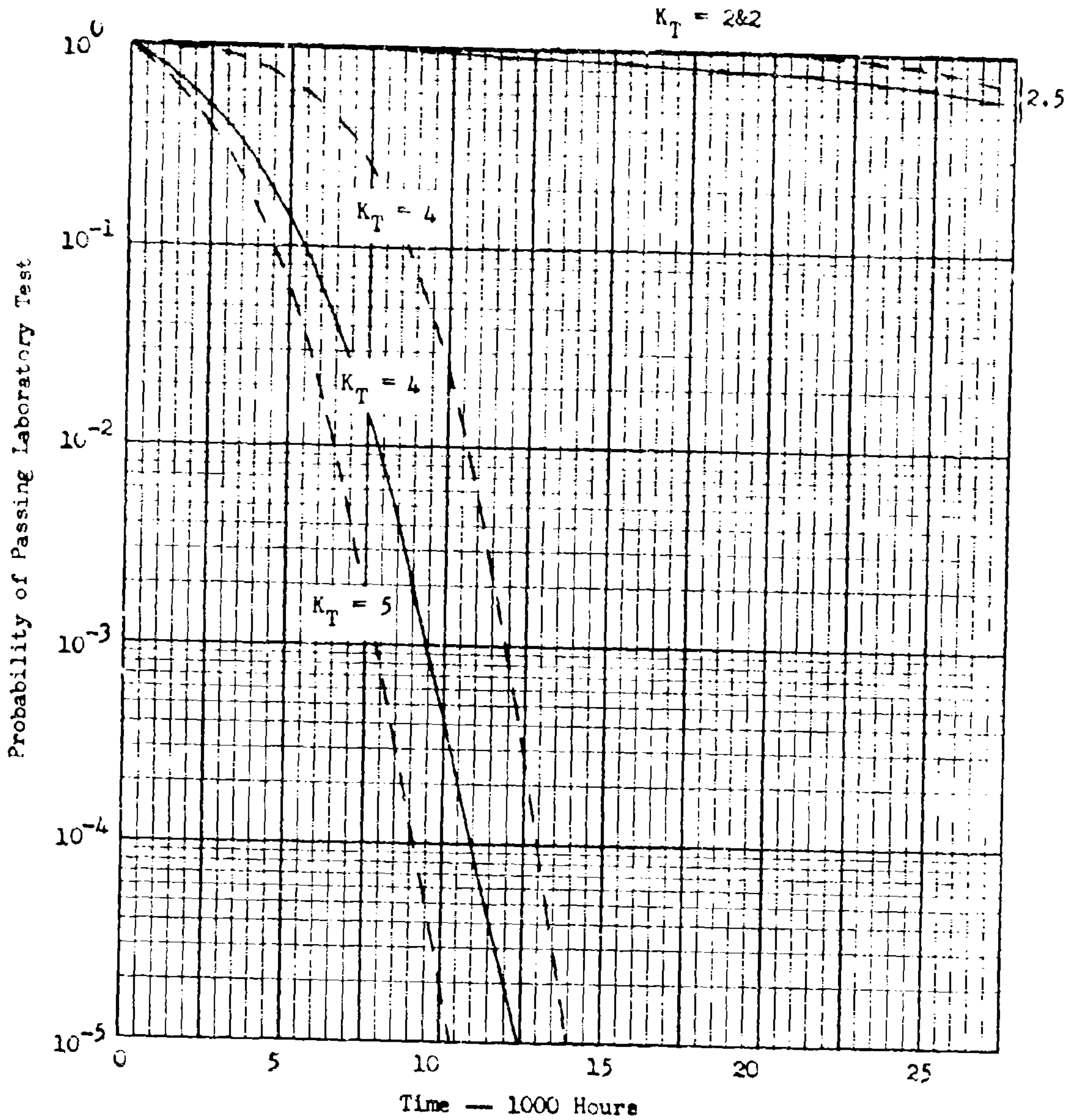


FIGURE 102. F-100 WING MIDSPAN COMPUTED FATIGUE STRUCTURAL RELIABILITY - FLEET OPERATION S-N SCATTER = 4

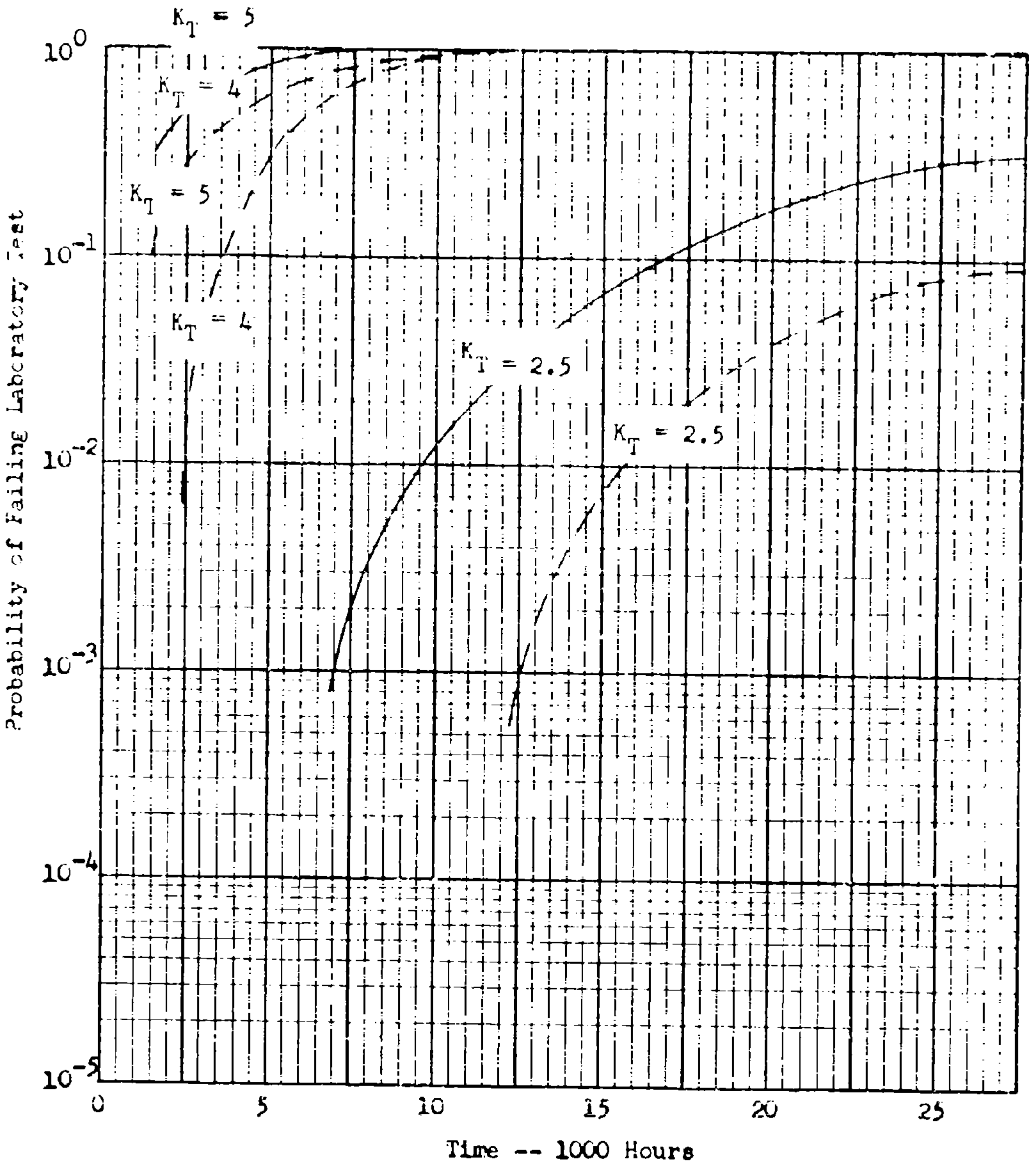


LEGEND

——— Probability of Passing Fatigue Plus Static Test

— — Probability of Passing Fatigue Test

FIGURE 103. F-100 WING MIDSPAN COMPUTED FATIGUE STRUCTURAL RELIABILITY - PASSING PROBABILITY, TEST OPERATION S-N SCATTER = 4

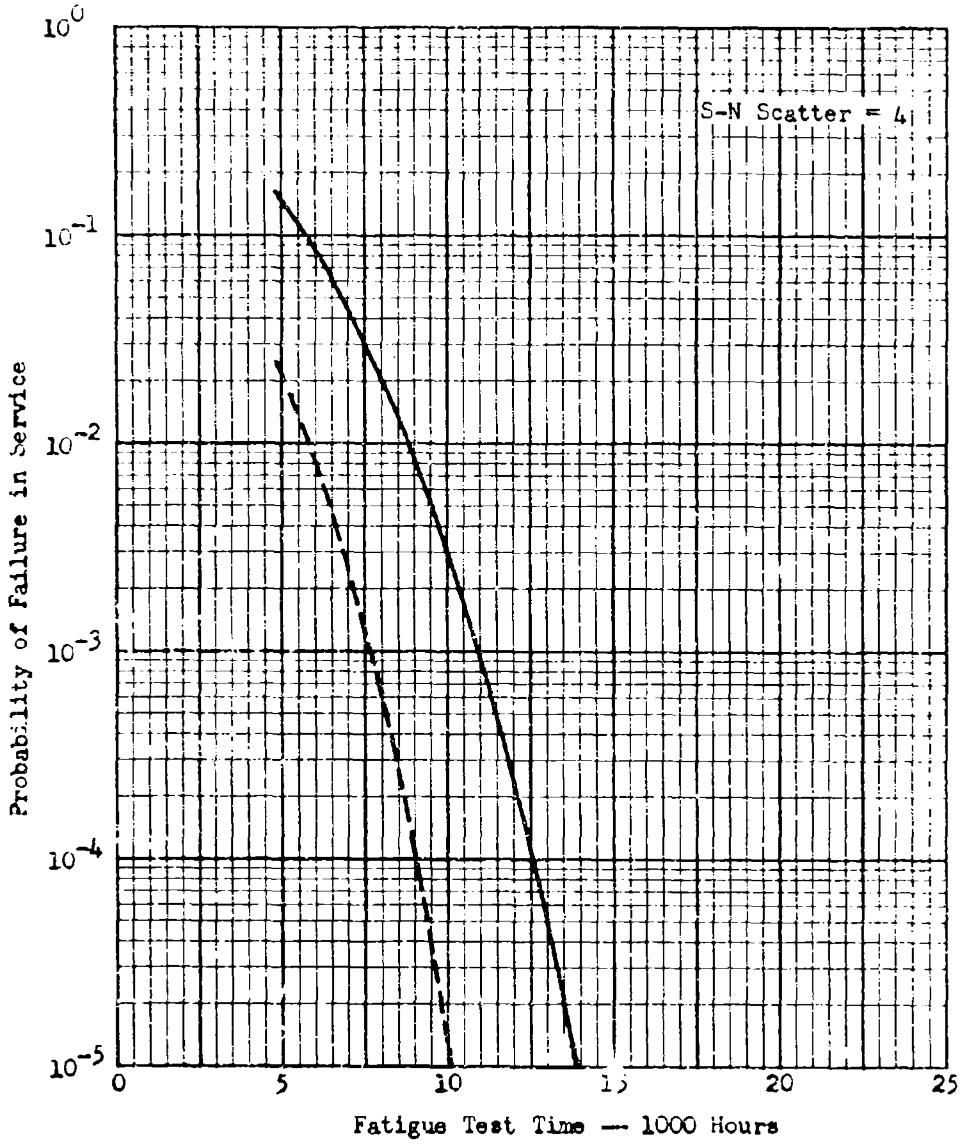


LEGEND

——— Probability of Failing Fatigue Plus Static Test

— — Probability of Failing Fatigue Test

FIGURE 104. F-100 WING MIDSPAN COMPUTED FATIGUE STRUCTURAL RELIABILITY - FAILING PROBABILITY, TEST OPERATION S-N SCATTER = 4



LEGEND

——— After fatigue test

— — — After fatigue test and static test

FIGURE 105. F-100 WING MIDSPAN COMPUTED FATIGUE STRUCTURAL RELIABILITY-FAILURE PROBABILITY AT A NOMINAL LIFE OF 5500 HOURS AFTER TESTS - FLEET OPERATION

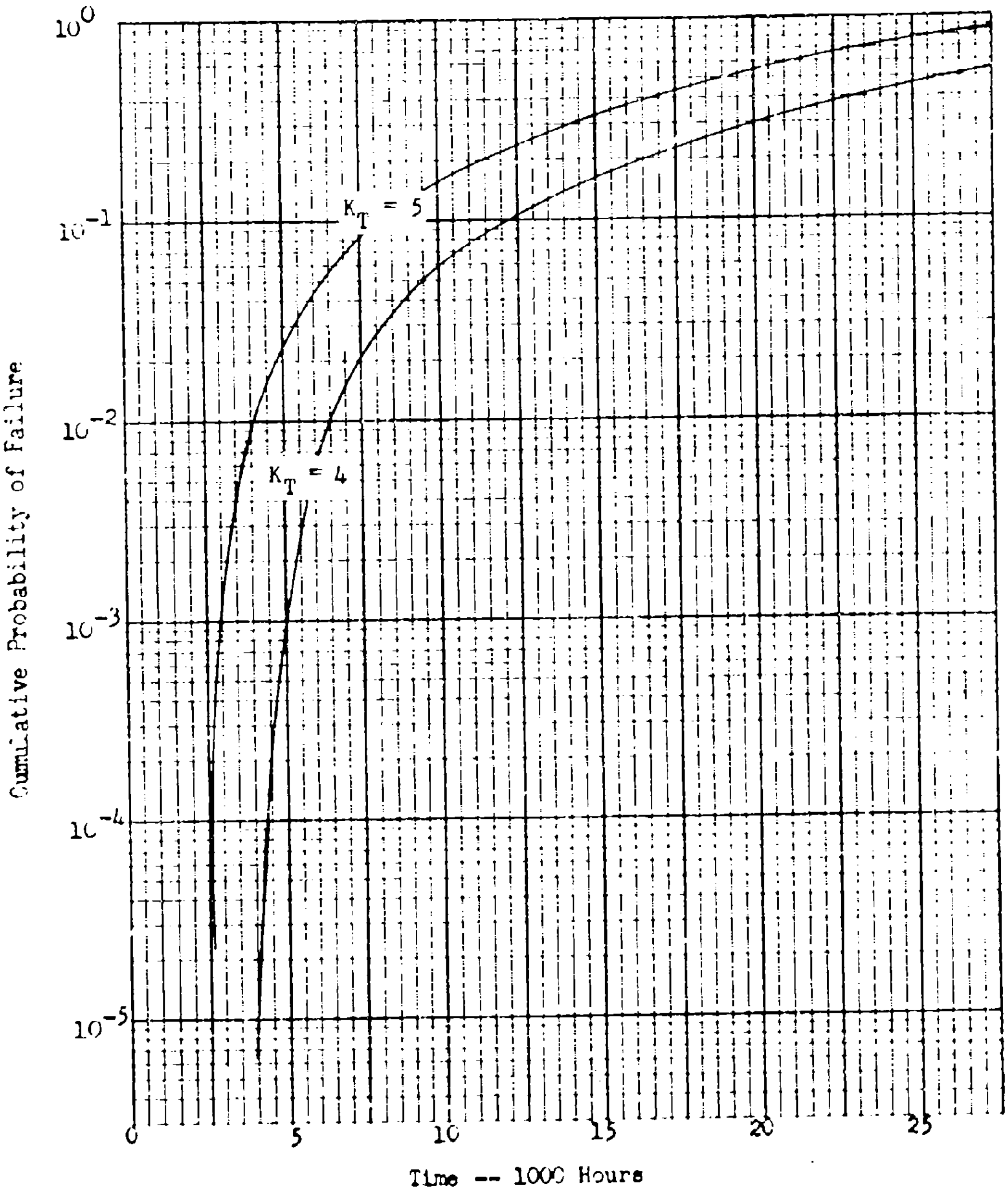
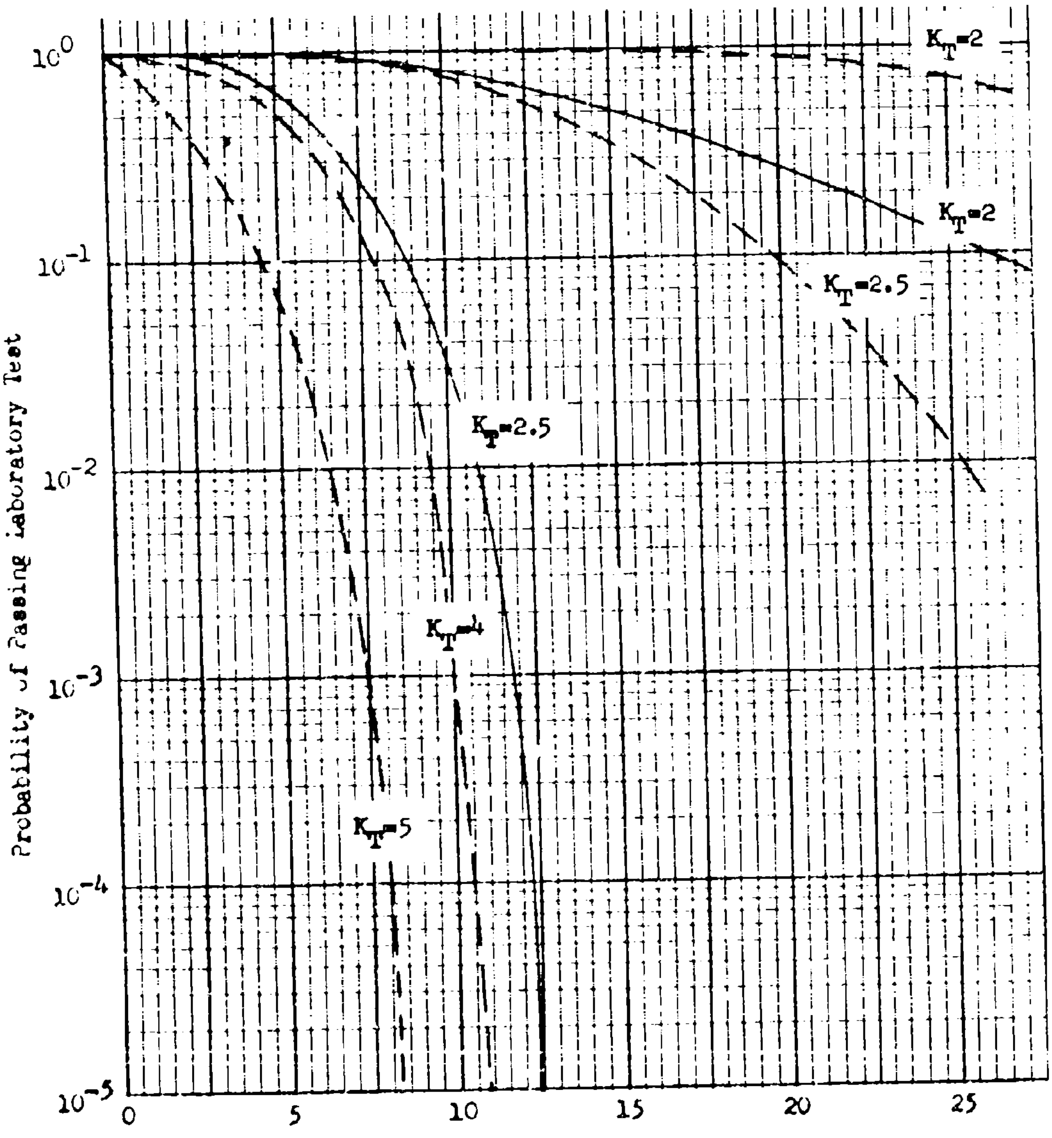


FIGURE 106. F-100 FUSELAGE STATION 310 COMPUTED STRUCTURAL RELIABILITY - FLEET OPERATION S-N SCATTER = 4

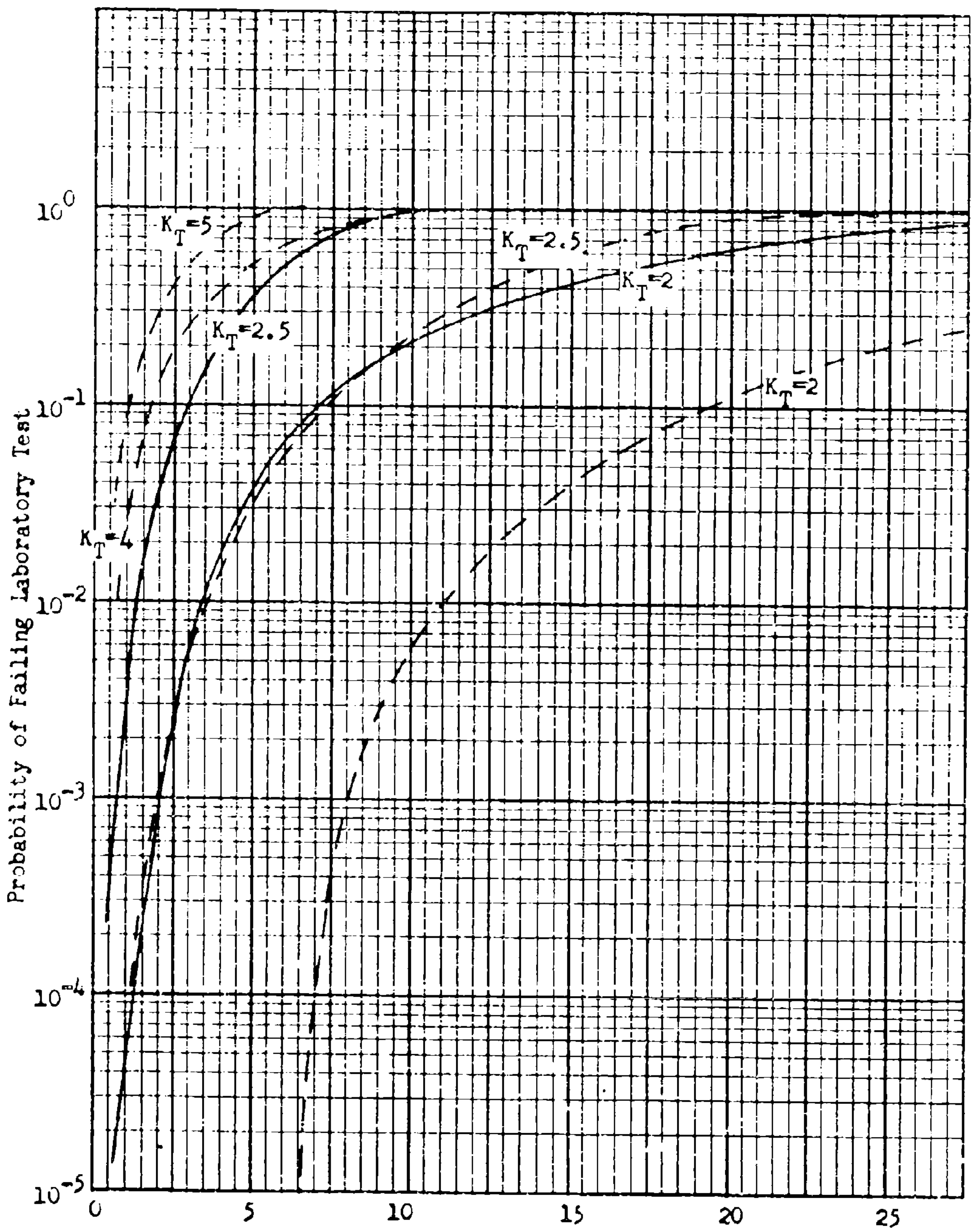


LEGEND

——— Probability of Passing Fatigue plus Static Test

-- — Probability of Passing Fatigue Test

FIGURE 107. F-100 FUSELAGE STATION 310 COMPUTED FATIGUE STRUCTURAL RELIABILITY - PASSING PROBABILITY, TEST OPERATION S-N SCATTER = 4

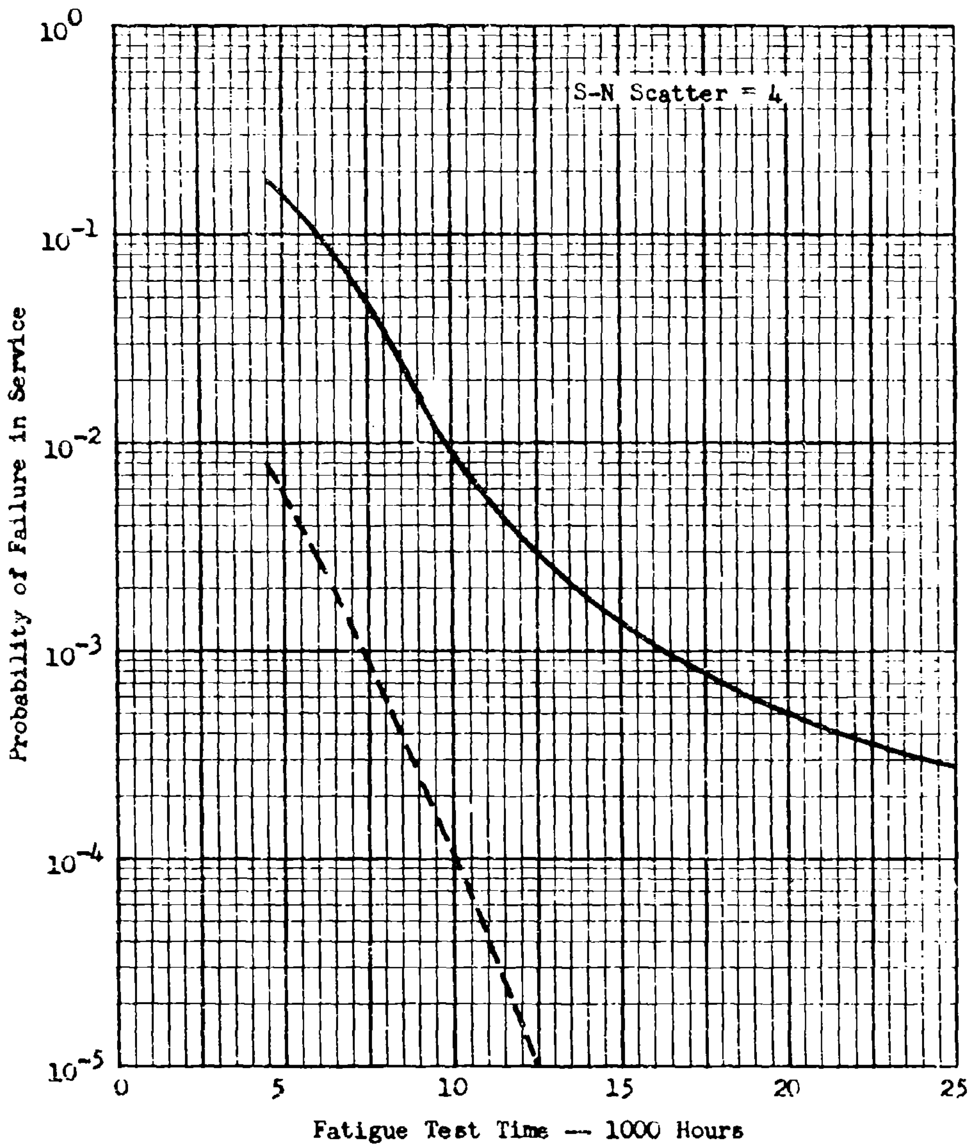


LEGEND

——— Probability of Failing Fatigue plus Static Test

— — Probability of Failing Fatigue Test

FIGURE 108. F-100 FUSELAGE STATION 310 COMPUTED FATIGUE STRUCTURAL RELIABILITY - FAILING PROBABILITY, TEST OPERATION
S-N SCATTER = 4



LEGEND

——— After fatigue test

— — After fatigue and static test

FIGURE 109. F-100 FUSELAGE STATION 310 COMPUTED FATIGUE STRUCTURAL RELIABILITY - FAILURE PROBABILITY AT A NOMINAL LIFE OF [illegible] HOURS AFTER TESTS - FLEET OPERATION

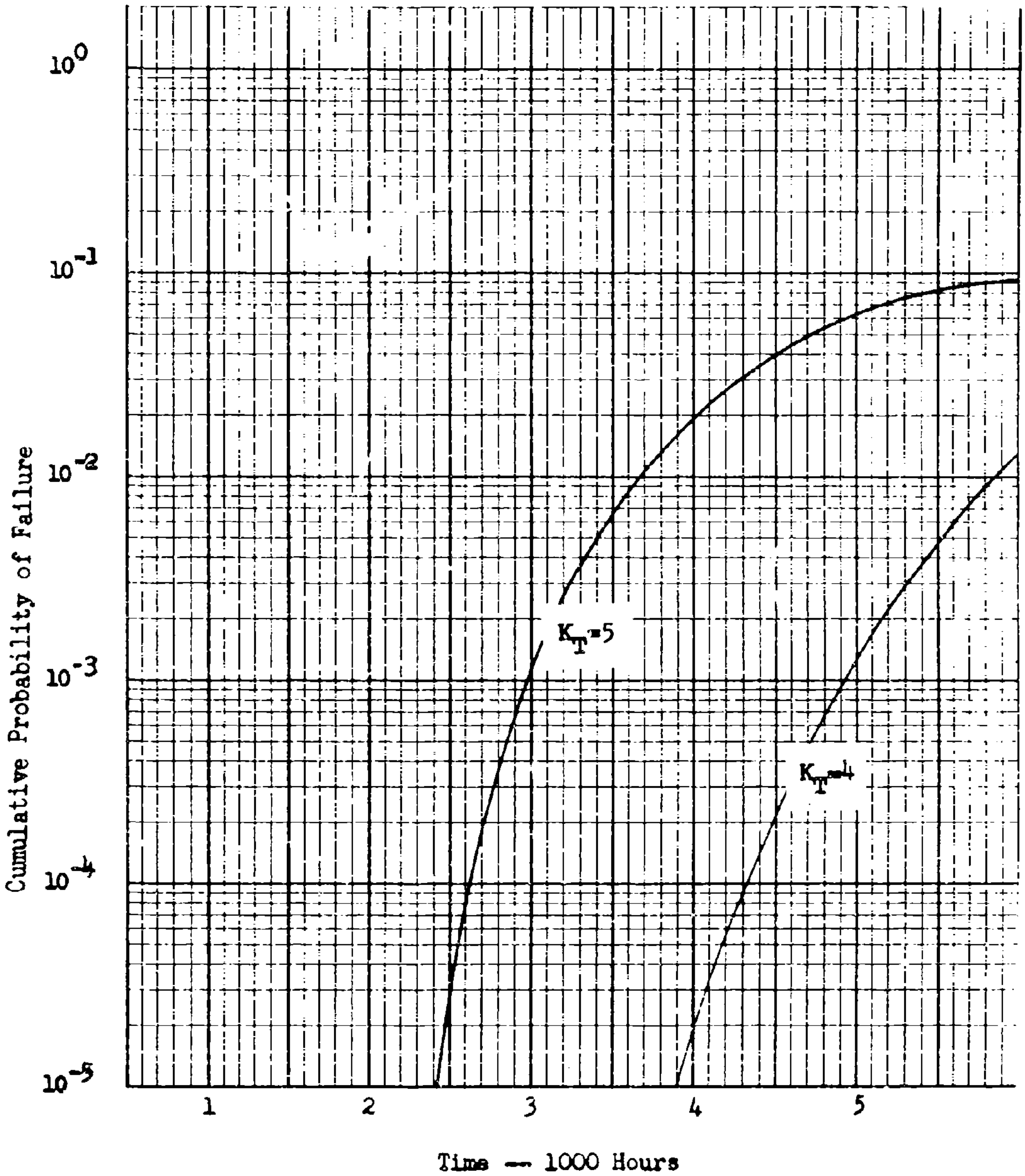
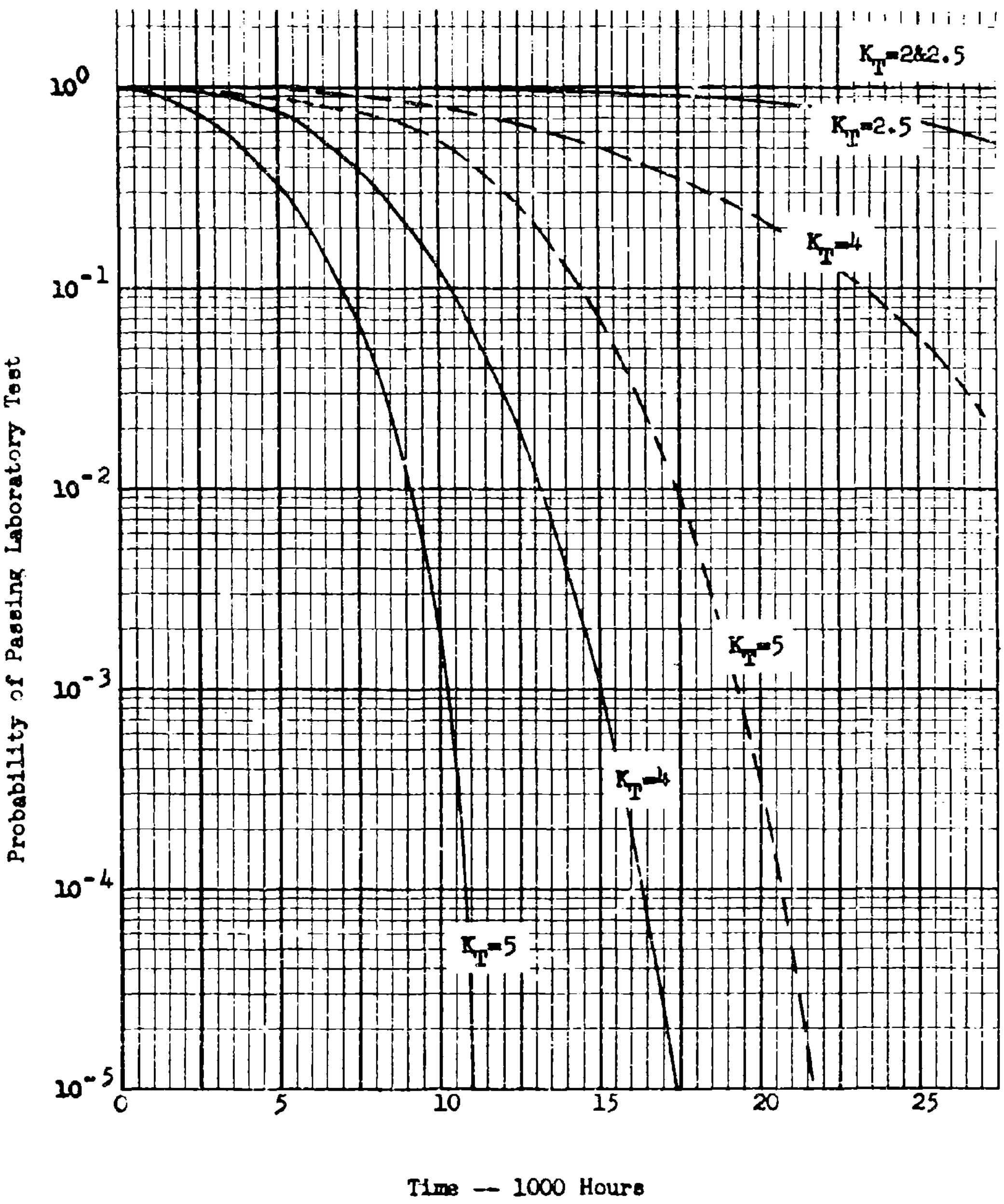


FIGURE 110. F-100 FUSELAGE STATION 369 COMPUTED STRUCTURAL RELIABILITY
FLEET OPERATION S-N SCATTER = 4

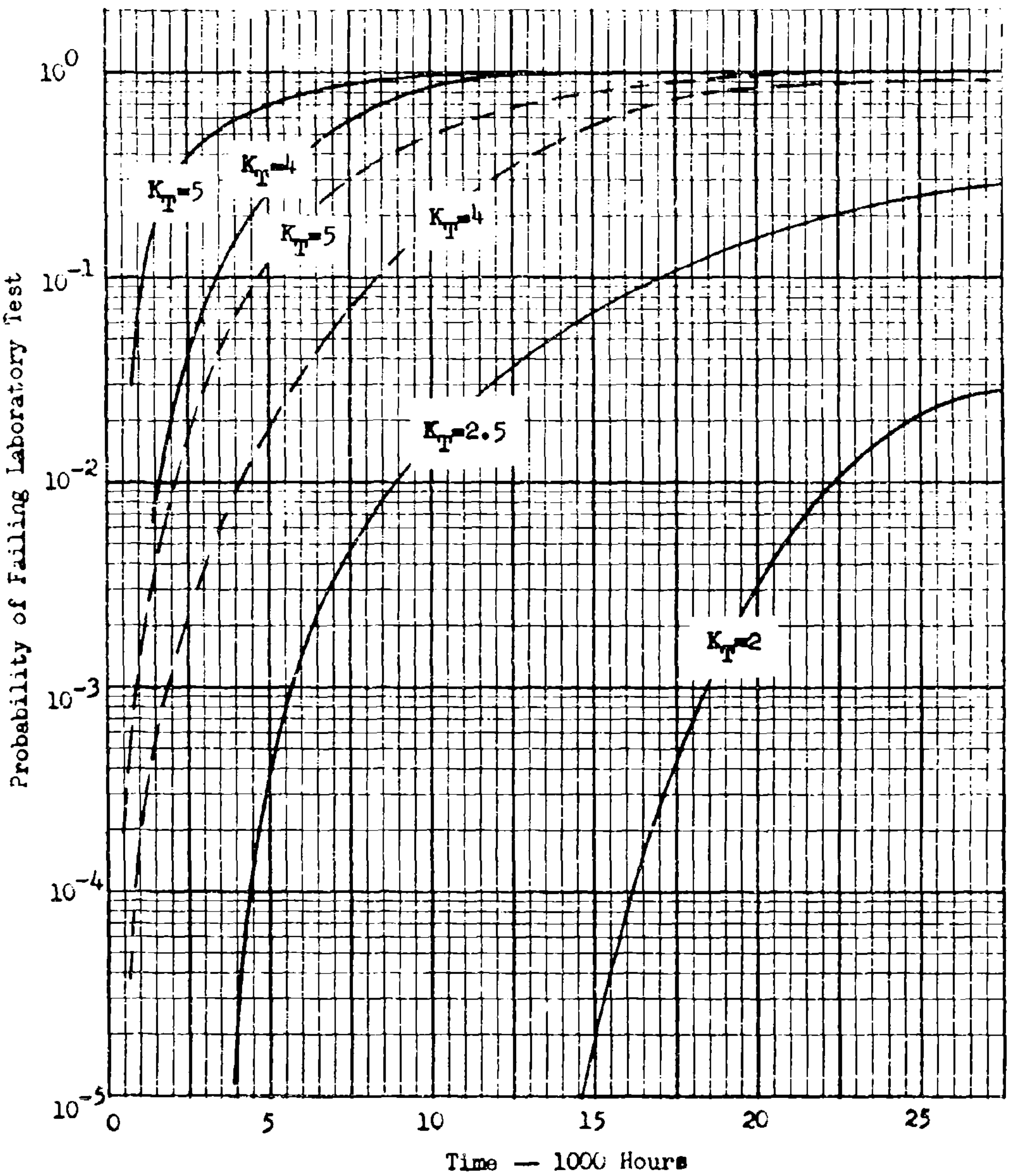


LEGEND

— — — Probability of Passing Fatigue Test

———— Probability of Failing Fatigue plus Static Test

FIGURE 111. F-100 FUSELAGE STATION 369 COMPUTED FATIGUE STRUCTURAL RELIABILITY - PASSING PROBABILITY, TEST OPERATION S-N SCATTER = 4

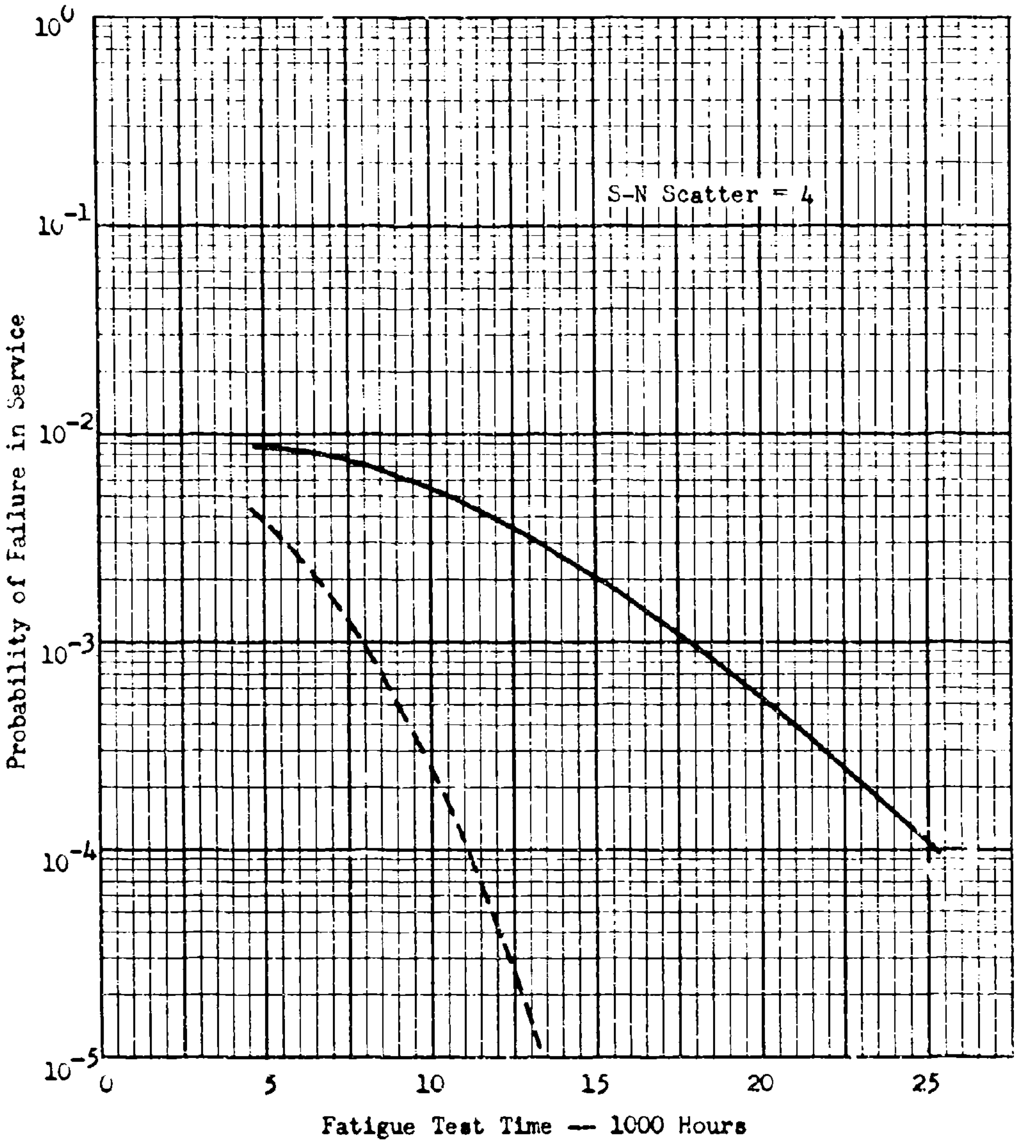


LEGEND

——— Probability of Failing Fatigue and Static Test

— — Probability of Failing Fatigue Test

FIGURE 112. F-100 FUSELAGE STATION 369 COMPUTED FATIGUE STRUCTURAL RELIABILITY -- FAILING PROBABILITY, TEST OPERATION S-N SCATTER = 4



LEGEND

——— After Fatigue Test

— — After Fatigue and Static Test

FIGURE 113. F-100 FUSELAGE STATION 369 COMPUTED FATIGUE STRUCTURAL RELIABILITY - FAILURE PROBABILITY AT A NOMINAL LIFE OF 5500 HOURS AFTER TESTS - FLEET OPERATIONS

6.6 CORRELATION BETWEEN COMPUTER PREDICTION AND OPERATIONAL EXPERIENCE

A new method for computing reliability of structures can be properly evaluated only if the results of the new method can be compared with known facts. One reason for including the F-100 data in the present study was to allow a comparison with data from a well-established successful operational airplane. In actuality, however, a satisfactory comparison becomes quite difficult. There are several reasons for this. First, as discussed in Section 6.3b, the exact number of "structural failures" cannot be determined from the records available. Second, operations with the F-100 are continuing so the failure rate to the end of the F-100 service life is not known at present. As was pointed out in Volume I, the actual reliability of a structure cannot be determined from the failure rate, even after the last flight of the last aircraft in the fleet. Third, the computed structural reliability figures are subject to all of the difficulties discussed in the previous sections of this report. However, a comparison of the best figures available to represent the operational experience with those predicted by the computer program as described in Section 6.5 will be most useful.

It was noted in Section 6.3b that the exact number of F-100 structural failures could not be determined, but it was decided there that 20 was an appropriate number to use. These failures have occurred during the 3,786,210 hours of F-100 operation as established in Section 6.3b. From these figures the failure rate (i.e., failures per hour) can be determined to be $20/3.7862(10)^6 = 5.282 \times 10^{-6}$. If it is assumed that the failure rate is a constant, the structural reliability for a stated service life can be approximated by using the Poisson law.[30, 31]

$$S.R. = e^{-\lambda T}$$

where

$S.R.$ = Structural Reliability

e = 2.7182

$$\lambda = \text{Failure Rate} = \frac{\text{Number of Failures}}{\text{Total Fleet Hours}}$$

T = Stated service life

If S.R. is large (greater than 0.9), the formulation can be simplified to

$$S.R. \approx 1.0 - \lambda T$$

From this and the failure rate determined above, it can be calculated that the structural reliability for F-100's whose service life is 2000 hours is 0.99. If the service life is extended to 5500 hours, the structural reliability would drop to 0.97. However, the ASIP program, described in Section 6.4a, is intended to increase the service life of the F-100's to 5500 hours. Additional fatigue testing and the ensuing modifications under the ASIP program should decrease the F-100 failure rate. Because of this the modified F-100's could be expected to have a higher structural reliability than the 0.97 value for 5500 hours.

As has been noted, the value of 20 for the number of failures to date in the F-100 fleet is somewhat arbitrary. If the true value is something other than 20, the structural reliability number would be changed. Figures 114 and 115 show how the S.R. would vary. It should be noted on Figure 115 that, if a 0.99 S.R. is to be attained at a service life of 5500 hours, no more than seven failures should have occurred at the present time.

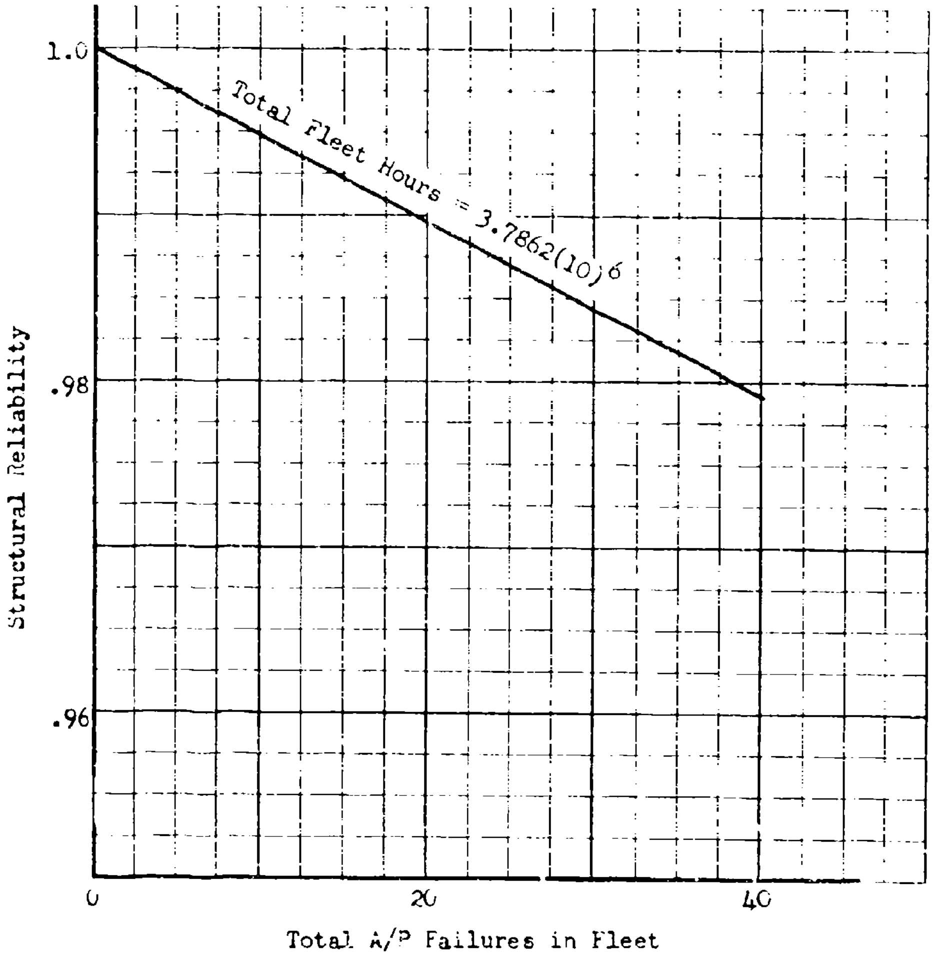
TABLE XXIII

F-100 COMPUTED FATIGUE RELIABILITIES

Fatigue Test Time	5500 Hours		11,000 Hours		22,000 Hours	
Item & Ref.	Fatigue	Fatigue and Static	Fatigue	Fatigue and Static	Fatigue	Fatigue and Static
Wing Root (Fig. 97)	.85	.908	.935	.991	.99993	$>.9_{10}$
Wing Root (Rev.) (Fig. 101)	.922	.955	.963	.9993	$.9_5$	$>.9_8$
Wing Midspan (Fig. 105)	.87	.986	.999	$>.9_5$	$>.9_{12}$	$>.9_{12}$
Fus. Sta. 310 (Fig. 109)	.85	.996	.994	.99995	.9996	$>.9_7$
Fus. Sta. 369 (Fig. 113)	.991	.997	.995	.9999	.9996	$>.9_8$

Results of the fatigue reliability analysis are given in Table XXIII. The reliabilities in this table are the reliabilities to be expected in service in a nominal 5500 hour lifetime following a fatigue test to one of the three test lengths indicated, also followed by a static test where indicated. Values are given for all five airplane locations included in the study. The most fatigue-sensitive location, the wing root, has a computed fatigue reliability of 0.85 after passing a fatigue test to 5500 hours. The figures on Table XXIII illustrate the benefits to be gained by extending the test time or by running a static test at the end of the specified fatigue test. Either method will assure a significantly improved fatigue reliability level of a structure that passes the prescribed tests.

The F-100 structural reliability as computed by the methods developed herein, static and fatigue, was based primarily on the measurements made in the Aircraft Structural Integrity Program. That is, the load and strength spectra at five locations on the airframes (two wing stations, two fusslage stations - one of which includes the horizontal tail - and the vertical tail root) were taken from the Air Force operational data. The static reliability



STRUCTURAL RELIABILITY, S.R. = $e^{-\lambda T}$

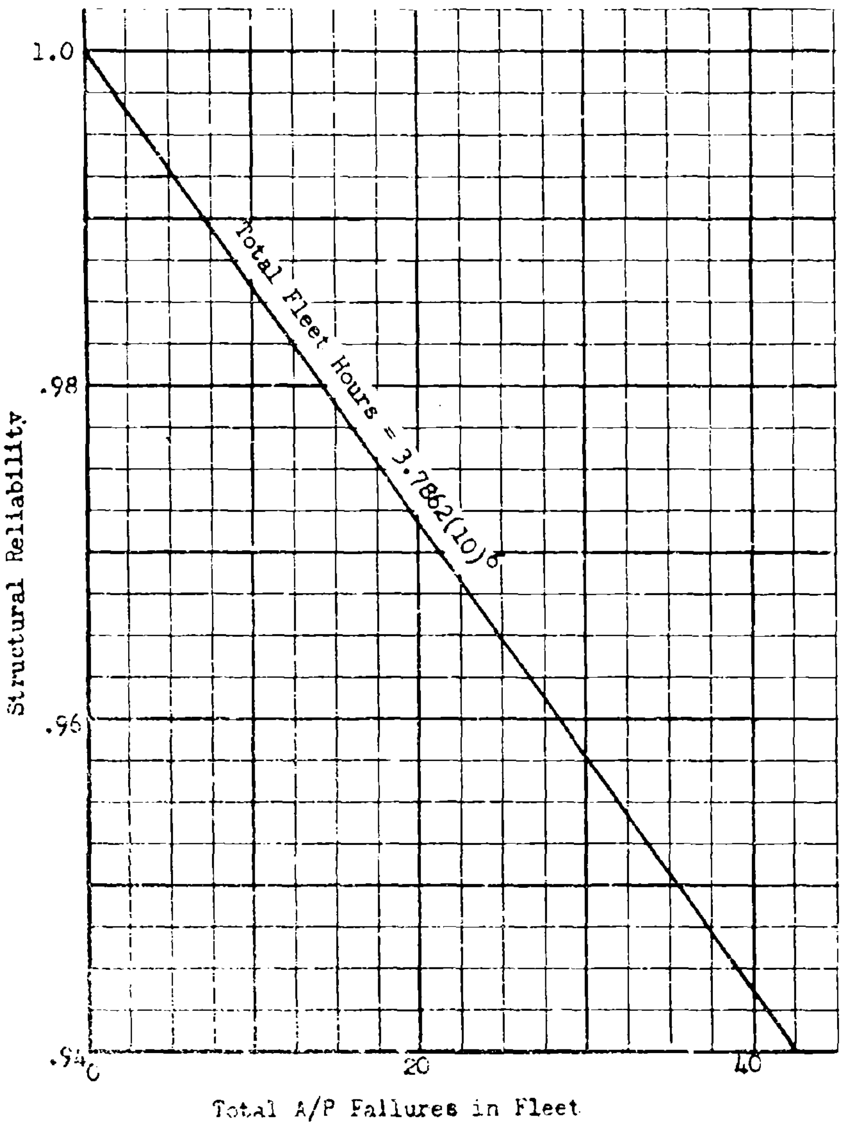
where λ = Failure Rate, per hour

$$= \frac{\text{Failed A/P's}}{\text{Total Fleet Hours}}$$

T = Service Life per A/P, hours

= 2000 Hours

FIGURE 114. F-100 FLEET STRUCTURAL RELIABILITY - 2000 HOURS



STRUCTURAL RELIABILITY, S.R. = $e^{-\lambda T}$

where λ = Failure Rate, per hour

$= \dfrac{\text{Failed A/P's}}{\text{Total Fleet Hours}}$

T = Service Life per A/P, hours

= 5500 Hours

FIGURE 115. F-100 FLEET STRUCTURAL RELIABILITY - 5500 HOURS

of the operational fleet, which was estimated on page 209 to be 0.99 at 2000 hours, is not inconsistent with the predicted results as summarized on Table XXII. Of those stations included in this analysis, the fatigue structural reliability as calculated with the computer program shows the wing root zone to be the most critical area on the airplane. This has been verified during the ASIP program. In Section 6.2c it is noted that a wing root failure occurred at 4674 hours. This test and failure together with the operational results show a most gratifying correlation with the structural reliabilities predicted by the FATREL computer program as summarized on Table XXIII.

SECTION VII

ADVANTAGES AND DISADVANTAGES OF THE NEW PROCEDURE

7.1 GENERAL

The new procedure, described in the previous sections of this volume, has many advantages over the Present System and over a Purely Statistical Structural Reliability System. Inevitably, there must be some problem areas in any new procedure. These advantages and disadvantages must be judged dispassionately to determine the true value of the new procedure. If the advantages do not outweigh the disadvantages, it would be illogical to implement the new procedure.

It appears that the new procedure retains the desirable features of the Present System while modifying the system to incorporate all of the characteristics recommended in Section 3.6 of Volume I. Most of the problem areas associated with the new procedure have always been problem areas. The new procedure does not create new problems, although it may recognize more clearly those that already exist.

7.2 ADVANTAGES

The basic advantage of the new procedure is its ability to logically establish the structural performance necessary to achieve a quantitatively definable goal. This permits a realistic definition of the minimum structure required to meet this goal. It also clearly indicates those structural and operational characteristics that will justify the use of less severe structural design criteria. Because each of these requirements is quantitized, trade-offs can be made evaluating the benefits of criteria reduction against the difficulties of providing the characteristics that will validate the criteria reduction. Other advantages are listed below:

a. **The new procedure represents a modification of the Present System, not a radical upheaval.**

Since the procedure represents a modification of the Present System, not a completely different approach, structural designers and analysts do not need to unlearn their present methods. The form of the structural design procedure is unchanged although the numbers and the meaning of the numbers may change. During the initial phases of implementing the use of the new procedure, numbers from both the old and the new procedures can be compared. This will result in greater confidence in the validity of the new procedure. It will mean that the changes from current procedures will be evolutionary rather than revolutionary.

b. Specific requirements in the new procedure are practical and easily administrable.

Although the new procedure recognizes the statistical nature of the functions involved, the requirements are deterministic. The choice of limit and omega conditions is based on the expected probability of exceeding the condition. Once the decision is made, the discrete condition becomes <u>the</u> requirement. Because the requirements are discrete, they can be administered effectively. Proof of compliance is a go, no-go proposition which results in a sharp line of demarcation between the acceptable and unacceptable structural system.

c. The structural and non-structural requirements are decoupled but there is a well defined interface between the two.

In a Purely Statistical Structural Reliability System, the requirements and responsibilities of the structural and non-structural system become so intertwined that it is impossible to administer the requirements. With the decoupling associated with definition of discrete limit and omega conditions, it becomes possible to make decisions. Even though a limit condition is intended to be a condition that is not exceeded very often, the designation of the condition as limit carries with it the connotation that the condition is the upper bound of what is expected and permissible. Therefore, once the limit condition is chosen, those concerned with the operation of the vehicle and the non-structural systems cannot be held responsible if a structural failure occurs at limit condition or less. Whether or not the limit condition is attained more frequently than expected becomes immaterial. The structural system is responsible for surviving the limit condition whenever it occurs. In the same vein, the structural system is not expected or required to survive beyond the omega condition. If a structural failure ever does occur due to exceeding the omega condition, the cause of failure must be attributed to an operation of the vehicle or non-structural system to a condition grossly beyond the specified permissible limit. Thus, the cause of failure and the appropriate corrective action will always be clear-cut. This is a prerequisite for an administrable system. In effect, a decision is made in advance in regard to how the structural system should perform to avoid failures under expected conditions and how the non-structural systems should perform by avoiding conditions where structural failures can be expected to occur.

d. The new procedure protects against the unexpected degradation of structural integrity that may result from the use of structural systems with large scatters in strength.

Current trends in structural design indicate a growing use of structural configurations predisposed towards a large scatter in strength. Structures operating near the extreme of the high-temperature capability of the material, large shell structures, and the use of brittle materials are becoming commonplace. These are all conducive to larger strength scatter than experienced in any structures of the past except castings. Since the new procedure recognizes strength scatter as an important consideration in the establishment of structural design requirements, it is most likely that sufficient provision will be made to accommodate whatever degree of strength scatter occurs in future structures.

e. The new procedure encourages reductions in the severity of the structural design criteria and, thus, the weight of the structure by stipulating the situations justifying such reductions.

The Present System has no mechanism to justify a reduction in requirements. At best, any attempt at reductions becomes a subjective action based almost entirely on judgment. The new procedure permits the reduction of design factors to any level desired but sets the conditions necessary to justify the reduction. This permits the designer the option of significant weight reductions provided the price is paid in terms of more careful control of operations and more stringent limitations on the structural configuration. Multiple test articles can be another justification for reducing the structural criteria if the cost and schedule problems involved can be accepted.

f. The new procedure provides for the examination and positive control of the environmental functions that significantly affect structural reliability.

By providing a line of demarcation between the regions where the structural and the non-structural systems are responsible for preventing failures, the way is opened to controlling the exceedance of the specified conditions. The structural criteria is transformed from a passive document that assumes that future vehicles will have the same structural and operational characteristics as past vehicles to a procedure that provides a framework for specifying the active steps to ensure that critical functions are controlled to provide the desired results.

g. The new procedure identifies a quantitative objective that leads to a consistent and logical relationship between all elements of the structural system.

A simple factorial relationship between limit and ultimate loads, as in the Present System, does not necessarily provide the capability in all components of the vehicle to survive the same operational condition. Therefore, some components are overdesigned relative to others. In the new procedure, the conditions to be survived are chosen and each component on the vehicle must survive the loads at that condition — no more and no less.

h. Fatigue and high temperature considerations are integrated into the new procedure following the same basic principles developed for the static conditions.

The approach to fatigue and high-temperature situations is handled as a simple extension of the philosophy developed for static conditions. There is none of the uncertainty exhibited in other proposed criteria for hot structures. The requirement is that most of the structures must survive the omega condition. This requires survival at the local temperatures which are determined for the omega condition. There is no factorial relationship between temperatures at limit and omega conditions. The temperatures at limit and omega are simply those appropriate to the two design conditions. The fatigue situation is comparable in that a high degree of reliability at the nominal or limit life is provided by designing and testing to multiples of the nominal life. Assurance that most of the structures will survive to a life substantially beyond the nominal life is obtained from the same design and test requirement that satisfies the limit requirement.

7.3 DISADVANTAGES

Any proposal to change structural design criteria procedures inevitably will encounter some arguments against making such a change. These arguments must be recognized and answered before there can be general acceptance of the new procedure. Some of the potential disadvantages and problem areas are listed in this section. It should be noted that it is not necessarily agreed that all items listed represent disadvantages or problem areas. However, the list contains most of the pertinent questions raised by those who have been exposed to the new procedure.

a. The proposed new procedure represents a change from the Present System.

It is a simple fact that change is always resisted — sometimes rationally, sometimes arbitrarily. It must be recognized that there is a built-in reluctance among all engineers to change any procedure that has been successful.

Therefore, the advantages must be clear-cut and the problems must be resolved so that there is no logical reason for resisting the change to the new procedure.

b. The new procedure calls for the definition of two sets of design conditions, limit and omega.

Traditionally, aerospace structural systems have been designed for a single design condition. The limit loads have been multiplied by a factor of safety to obtain ultimate loads. These ultimate loads are still considered to be associated with the velocity, load factor and other parameters at the limit condition. In the new procedure, an omega condition may specify different velocity, load factor and other parameters from those at the corresponding limit condition. It does not appear that this is a radical departure from present practice. It is not unusual to perform an analysis at limit for buckling or yielding and a separate analysis at ultimate for total rupture. Conceptually, separate limit and omega condition analyses are no different than the analyses performed for any two conditions at present, such as a high-speed and a low-speed flight condition.

c. The analysis of the extra conditions may cost more and take longer.

The added requirements for two sets of conditions undoubtedly will require more analysis than before. However, in most cases, it should be possible to decide by inspection whether the limit or the omega condition is critical. This same procedure is used now to reduce hundreds of potentially critical conditions to ten or twenty that are analyzed in detail. Whatever extra cost is involved will have to be recognized as the price paid to gain the advantages listed in the previous section.

d. Establishment of requirements for an omega condition beyond the limit condition represents an extension of structural responsibility into operational regions not considered in past practice.

Actually, the omega condition requirement is not as great a break with traditional design practices of the past as it may seem on the surface. For those design conditions governed by multiplying limit loads by the factor of safety, some overload capability has always been available. Although the amount of structural capability was fixed, the amount of operational capability was not. In special situations, where the increment in operational capability was obviously small, ultimate conditions have been specified in the past. The landing gear situation represents a well-known example of this. Even if the landing gear has the strength capability to withstand 150 percent of the limit loads, it may fail at an impact velocity very slightly higher than the limit velocity. For one thing the energy involved increases

as the square of the impact velocity. Possibly more important is the fact that the energy absorption characteristics of the landing-gear system are critically dependent on such things as the geometry of the gear linkage, bottoming characteristics beyond the normal stroke, and the design of metering pins.

The need for an omega condition in a statistically based procedure stems from the fact that most failures in mature structural systems (after any initial defects have been uncovered and corrected) are caused by conditions substantially beyond the limit conditions. Figure 26 and the discussion in Section 2.3a(1) and 2.3f show that most failures will occur close to the omega condition and that the probability of failure approximates the probability of exceeding the omega condition. If conditions beyond limit were ignored, any probability of failure or structural reliability so determined would be meaningless. Thus, if quantitative structural design criteria by statistical methods is a valid objective for the new procedure, omega conditions or their equivalent must be considered. The only question is what form this consideration should take.

e. A requirement for structural capability at omega conditions might lead to a requirement for operational capability at these conditions.

Concern has been expressed by responsible industry personnel that definition of an omega condition for structural design might lead to operational requirements for the same condition. It is impossible to control what future responsible authorities will do. However, the logic of the situation should discourage any such action. The omega condition, by definition, represents an abnormal operational condition, whereas the limit condition represents the upper bound of normal or expected operational conditions required to satisfactorily perform the vehicle's mission. It does not seem reasonable to establish any operational performance requirements for an abnormal condition, attained only as a result of an operational error. All efforts should be directed toward avoiding the omega condition in order to avoid the failure to be expected at the omega condition.

f. Calculation of loads at the omega conditions will introduce many new problems into the design process.

It is undoubtedly true that there will be difficulties in calculating omega loads. Deformations will be larger than at limit and in many cases will be in the permanent deformation range. It is expected that experience in such analysis will relieve the problem to some extent. It seems more rational to face the problem squarely and make the best effort possible. It is inconceivable that qualified

engineers could not develop satisfactory analytical techniques to solve this problem. The alternative of accepting whatever overload capability happens to result from indirect requirements does not seem to be compatible with the logic of a quantitative structural design criteria.

g. The conventional factor of safety provides blanket coverage for situations that might not be recognized in a more sophisticated procedure.

Past experience has shown that this is a very real danger. There is such a thing as being rational to the point of impracticality. Concern over making this type of mistake cannot be dismissed lightly. Extreme care must be taken during the transition period between use of the Present System and implementation of the new procedure. The problems of implementation should be eased by the similarity between the two systems. The design requirements under the new procedure can be compared directly with those for the Present System. If there is ever a drastic difference, this should be a signal for caution. The reasons for the difference should be determined and the requirements re-examined. Significant differences in the requirements of the two systems should not be accepted uncritically. This does not mean that such differences, either in the direction of more critical or less critical requirements, cannot be justified under appropriate circumstances.

h. The new procedure requires a determination of the strength scatter, γ_s, of the structure.

The discussion of Section 2.3 makes it clear that the strength scatter, γ_s, is a significant parameter in the development of structural reliability. There has not been much formal documentation of the γ_s function in the technical literature. Nevertheless, there are data available, usually as a by-product of other studies, on the strength distribution of various materials. Although information on the strength scatter of fabricated components is less available, some does exist. A few programs such as those reported on Table 3 of Reference 29 furnish valuable information on the strength scatter of components. These data can be supplemented by organizing data where multiple tests have been run such as a series of box beams at different temperatures or large shell structures with various R/t ratios. If an envelope representing the upper and lower range of the test data can be drawn using engineering judgment, such data can furnish a satisfactory approximation of the strength scatter coefficient, γ_s. The range between the upper and lower envelopes of a typical quantity of data approximates the $\pm 2\sigma$ range. Therefore, the increment in value from lower to upper envelope can be divided by 4.0 to obtain σ and then divided again by the midpoint value to obtain γ_s. Such a technique is not very elegant and might not be rigorous enough

to satisfy a statistician, but it provides a reasonable engineering solution. It is believed that enough data is available now to begin implementing the new procedure. Once the need for data on strength scatter is established, the availability of such data can be expected to increase rapidly.

i. The new procedure does not solve the problem of how to avoid the failures that often accompany the early phases of the development of a new vehicle.

No procedure in the world can guarantee that mistakes will not be made. Structural design criteria can and should make provision so the structure can tolerate a reasonable level or error or discrepancy in the design, fabrication, and operation of a vehicle. This capability must necessarily be very limited or the criteria will require an excessively heavy structure. In any event, structural design criteria should define requirements that the structure is obligated to meet. Whether the design meets the obligation with the first structural configuration or whether the design cycle must be iterated many times is immaterial to the requirements. The number of iterations depends on the technological skill of the designer and analyst.

SECTION VIII

CONCLUSIONS AND RECOMMENDATIONS

8.1 CONCLUSIONS

A new procedure for defining statistically-based, deterministic structural design criteria has been developed and is presented in this volume. This new procedure incorporates all of the characteristics recommended in Section 3.6 of Volume I as desirable for a structural design system. The procedure represents a modification of the Present System, not a radical upheaval. As a result, the proposed structural design criteria are practical and easily administrable.

A new philosophy has been formulated to describe the function of structural design criteria. This new philosophy leads to a clearer understanding of the objectives of structural design as implemented in structural design criteria. The essence of this new philosophy is that a designated level of structural reliability can be attained by providing for structural survival in two specified situations. The first is that "no" failure should occur at a condition defined as a limit condition. Since limit conditions are designated as permissible and expected to occur relatively frequently, the structural system must have the capability to survive these expected conditions with near certainty if a high degree of structural reliability is to be attained. To provide against the possibility of an under-strength structure, the structural system should be designed to withstand design loads significantly higher than those at the limit condition. The magnitude of the increment or factor over limit is chosen so that an understrength of that amount will be rare relative to the desired level of structural reliability. The factor is a discrete number defined by the strength scatter of the structure and by the structural reliability desired.

Even perfect reliability for the limit conditions would not necessarily result in an overall low failure rate that would be acceptable. Most of the designated limit conditions will be exceeded on occasion, due either to vehicle operation beyond the prescribed operational limitations or to malfunctions and out of tolerance situations on subsystems that affect the structural environment. Accordingly, the second major structural provision as established by the new philosophy is for "most" of the structural systems to survive conditions that are a specified increment beyond the limit condition. The conditions associated with these overload situations are designated omega conditions in this report. The omega condition should represent a gross exceedance of the limit condition and should occur very rarely. If the frequency of exceeding the omega condition in actual operations is rare, then structural failure will be rare and the desired level of structural reliability will be attained.

The requirements for the new procedure are in the same format as those in the Present System so that designers and analysts do not need to unlearn their present methods. Where the structural and operational situations are

comparable to those of the past, the new requirements will be essentially unchanged. Where the strength scatter is unusually low, where more than one test article can be tested, where the overloads can be controlled, or where a lower structural reliability can be accepted, the new procedure will justify use of less severe structural design requirements. If the strength scatter is unusually large as in the case of hot structure operating near the upper limit of the temperature capability of the material, or with brittle structures, or with systems which are very sensitive to minor geometrical variations as in buckling of large shell structures, the additional design requirements needed to maintain a constant level of structural reliability are defined by the new procedure.

If it is desired to provide the Present System with a quantitative objective and with the capability to systematically resolve the problems associated with structures for advanced vehicles, the structural design system described in this report is needed. The new procedure retains the deterministic type of requirements that give the Present System its practicality and administrability. The deterministic requirements are established in such a way that they correspond to a structural reliability goal without having to prove directly that the goal has been achieved. In such an approach, all of the elements affecting structural reliability are consistently directed towards achieving the quantitatively defined structural reliability goal without introducing the impossible problem of proving compliance with a structural reliability requirement. The procedure described in this report is expected to accomplish this result.

6.2 RECOMMENDATIONS

It is recommended that a carefully planned program be instituted to gradually implement the new procedure described in this report. It would be unrealistic to expect that a new procedure with many unexplored ramifications could be substituted abruptly for the time-tested approach incorporated in present structural design criteria. Engineers are traditionally suspicious (and justly so) of new, "cure-all" procedures that ostensibly are more rational than the old procedure. Bitter experience has indicated that a "rational" procedure may be rational only in a limited area. Frequently, there are considerations that are covered by empirical requirements without an explicit definition of such coverage. A new procedure may not recognize the need and inadvertently eliminate the necessary coverage. There is no reason to believe that such a situation exists in the procedure recommended in this report but the possibility suggests the need to proceed cautiously.

It appears that the most advantageous scheme for implementing the general acceptance of this new philosophy and procedure would be to apply it on a limited scale initially. After some experience has been gained in using the procedure, consideration could be given to expanding its usage. This would permit all concerned to gain confidence in the proposed procedure as a useful approach to the structural design problem. The impact that the new procedure might have on cost and schedule could be assessed from the experience gained during this suggested small-scale implementation effort.

A limited effort to apply the procedure to actual designs might be obtained in one of two ways. The new procedure could be specified as a permissible alternate to the present procedure. Specific concurrence by the Procuring Agency could be required for each use of the new procedure. This implementation approach would almost certainly result in the new procedure being used only when it was less critical than the present procedure. However, the requirement for Procuring Agency concurrence would ensure that any such reduction would be subject to close scrutiny before acceptance.

A second plan for implementation would be to choose a specific vehicle and establish a requirement to perform a parallel but separate study of the design requirements using the new procedure. These requirements could be compared with those generated under the present system to determine whether the new procedure would result in adding or subtracting structure from a structural system already satisfying the present criteria.

If the proposed new procedure is deemed worthy of continued development, there are a number of steps that are recommended to aid in the process of implementation. Some of these are listed below.

a. The new procedure should be reduced to the precise language of a specification comparable to MIL-A-8860.[27] In this form, all concerned can make a better assessment of the impact of the new procedure.

b. A concerted effort should be started to assemble the data presently available on the strength scatter of materials and fabricated components. Steps should be taken to obtain new data as necessary to fill the gaps in the available data. In particular, more data are needed on the scatter in residual strength in fatigue situations.

c. Develop better analytical capability to predict the residual strength in fatigue situations. The residual strength method adapted from Reference 12 as described in Section 3.2 of Volume III must be considered to be a first-generation solution to the problem. Improvements can be expected to follow any serious attempt to use the residual strength concept in actual design.

d. More study is needed to develop precise rules governing the choice of limit and omega design conditions in a multiple parameter environment. Such cases have not been considered explicitly in the examples presented in this report. Validation of the limit and omega design conditions, as shown on Figure 46, comes as a result of a decision that the actual operations are consistent with the initial predictions used in choosing the design conditions. The actual results depend on the effectiveness of the controls on operations as indicated on Figure 45. When multiple parameters are involved, operational control of these parameters

usually resides with more than one non-structural system. The interface problems resulting from this situation need to be explored further.

e. It appears that more explicit control of the strength operations affecting the structural environment would improve the structural design situation. It is possible that a PERT-type operation to ensure that the various decisions shown on Figures 40 through 48 are made at the proper organizational level and at the proper time might result in more reliable structural systems for less weight and cost. The problems associated with establishing such a procedure should be explored further.

f. The computer program for calculating structural reliability, as presented in Volume III, starts with a factor of safety and prints out the resulting S.R. To determine the TFS required for a given S.R., as in the curves of Figure 12, it is necessary to iterate for several trial solutions to obtain the desired results. It would be a useful expansion of the program if the option could be added so the program would automatically perform the iteration. Then, a desired S.R. could be input and the TFS required for that S.R. would be calculated in a single operation.

g. It was suggested in Section 2.3e that it would be desirable to modify the computer program of Volume III to include a loads error function comparable to the strength function discussed in Section 2.3c. This would permit a computation of the conditional structural reliability before and after a flight loads measurement program. On Figure 43 it is noted that a decision must be made as to the adequacy of the strength test to simulate the failure modes properly. It is believed that the introduction of a quantitized value for this simulation adequacy into the computer program would make the calculated structural reliability more nearly correct. This would make provision for an assessment of the type of test in comparison to previous test experience, of the effects of scale models rather than full-scale test articles, and of other things such as time and temperature effects. An error function for the statistics governing the choice of limit and omega design conditions could be introduced into the computer program. Then, as data on the actual operational usage were obtained to validate or raise questions about the design conditions as discussed in Sections 2.3f and 2.3g(3), the computer program would automatically update the structural reliability values. The conditional reliabilities and the net structural reliability could be programmed for visual display on a Cathode Ray Tube (CRT). An easily interpreted picture could be generated of the status of the structure at each stage in its development and as it is expected to be after completion of all tests. This picture would be comparable to Figure 116.

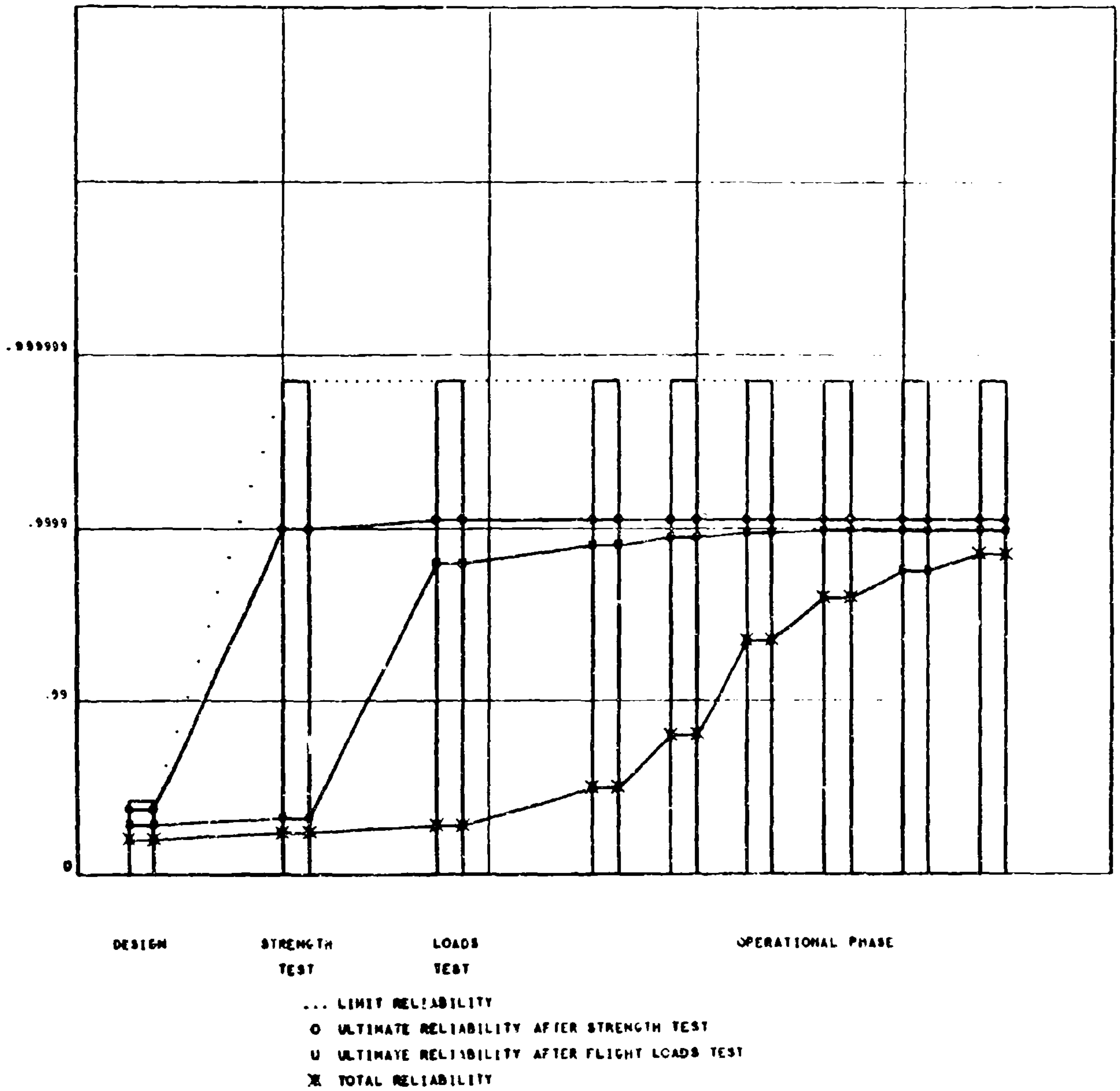


FIGURE 116. STRUCTURAL RELIABILITY GROWTH

h. The curves defining the design and test factor of safety such as Figures 12 and 24 are based on designing to the same load as the structure will be tested to. There is a potential weight saving if the requirements for design are lowered at the same time the test value is increased. This would result in more test failures but the final reliability would be maintained. This would give the designer another option if the increased cost and schedule delay due to the extra test failures are acceptable in order to gain some weight reduction. Further study of this procedure is recommended.

i. The philosophy presented in Section II is an outgrowth of the critique presented in Volume I. This critique discussed the problems associated with the procedures advocated in 14 individual documents. It is suggested that the authors of these documents be solicited for comments, both on the critique of their paper and on the new procedure proposed in this report. These comments could be published at a later date as an addendum to this report. Such discussions should be helpful in developing a consensus of what is the best procedure for future structural design criteria.

j. A study of the controls and procedures that would lead to being right the first time might be very useful in reducing net cost and time for developing a new structural system. Such a study could be accomplished within the framework of the Decision Network presented on Figures 40 through 48.

k. The recognition of errors, their type and their frequency is vital to establishing rational criteria. It is suggested that the data presented in Reference 6 be updated to include tests at contractors' plants plus those for other agencies such as NASA and USN. This would provide data that could justify or repudiate the contention that structural design is becoming more precise due to the extensive use of computers. The answers would be reflected in revisions to Figure 5 which serves as the basis for the strength error function programmed into the routine presented in Volume III.

l. A study of the weight minimization possible by a rational reduction of structural design criteria might be very productive. It appears that weight reductions of the same order of magnitude as those achieved from more efficient structural design may be possible.

m. At the present time some of the matrices used as input data for the fatigue reliability program (such as Tables IV and V in Volume III) are hand calculated. The computer program could be modified to do these automatically. Addition of a built-in error function comparable to the Figure 5 function for the static program would make the fatigue program easier to use. The present program requires a judgment choice of values for PK (See pages 108 and 131 of Volume III).

n. Section VI discusses some of the difficulties encountered in determining the structural failure rate for a particular fleet of airplanes. It is recommended that the data-gathering procedure be reviewed to see if the results could be provided in a format more useful to structural reliability analysis.

o. Whether or not the particular procedure presented in this report is adopted, it is recommended that an aggressive program be established to develop and implement structural design criteria that will define the structural performance necessary to achieve a quantitatively definable goal.

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13. ABSTRACT Exploratory research, needed to develop quantitative structural design criteria for aerospace vehicles, has been conducted to relate the probabilistic nature of design, operational, and environmental experiences to the structural performance of aerospace vehicles. Volume I presents a critique of present and proposed approaches to structural design criteria. Volume III formulates two computer programs for the procedure and presents the user's instructions for the programs.

Volume II develops the philosophy of a statistically-based, deterministic system. This forms the foundation of the recommended new procedure, which is a modification of the Present (Factor of Safety) Structural Design System, not a completely different approach. The concept that the structural system is expected to have the capability to survive both overload and understrength situations is propounded. Requirements for providing these two capabilities are identified separately and explicitly. These requirements are based on statistical considerations, but the resulting design conditions are established as deterministic requirements. This is the key to making the new procedure practical and administrable. A one page summary of the procedure is presented on page 122. An application of the procedure to the F-100 airplane demonstrates how to use the technique. Problems that may be encountered in implementing the procedure are discussed.

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